

Durham Research Online

Deposited in DRO:

01 November 2019

Version of attached file:

Accepted Version

Peer-review status of attached file:

Peer-reviewed

Citation for published item:

Liu, Guanshi and Toll, D. G. and Kong, Lingwei and Asquith, J. D. (2019) 'Matric suction and volume characteristics of compacted clay soil under drying and wetting cycles.', *Geotechnical testing journal.*, 43 (2).

Further information on publisher's website:

<https://doi.org/10.1520/GTJ20170310>

Publisher's copyright statement:

This is a preprint of an article published in *Publication Geotechnical testing journal*, Copyright © 2019 ASTM International, West Conshohocken, PA, DOI: 10/10.1520/GTJ20170310, www.astm.org.

Additional information:

Use policy

The full-text may be used and/or reproduced, and given to third parties in any format or medium, without prior permission or charge, for personal research or study, educational, or not-for-profit purposes provided that:

- a full bibliographic reference is made to the original source
- a [link](#) is made to the metadata record in DRO
- the full-text is not changed in any way

The full-text must not be sold in any format or medium without the formal permission of the copyright holders.

Please consult the [full DRO policy](#) for further details.

*G. Liu, D. Toll, L. Kong, and J. Asquith, (2019) "Matric Suction and Volume Characteristics of Compacted Clay Soil under Drying and Wetting Cycles," Geotechnical Testing Journal 43.
<https://doi.org/10.1520/GTJ20170310>.*

Matric suction and volume characteristics of compacted clay soil under drying and wetting cycles

Guanshi Liu

Research Associate (Associate Research Fellow), Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Xiaohongshan, Wuchang, Wuhan 430071, P.R. China

D.G. Toll¹

Professor, Department of Engineering, Durham University, Durham, DH1 3LE, UK.

Lingwei Kong

Professor, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Xiaohongshan, Wuchang, Wuhan 430071, P.R. China

J.D. Asquith

formerly Research Associate, Department of Engineering, Durham University, Durham, DH1 3LE, UK.

Abstract: The influence of drying and wetting cycles on matric suction and volume characteristics of a compacted low plasticity clay soil was studied experimentally. An apparatus was developed where soil specimens were placed in direct contact with a high suction tensiometer, then repeated drying and wetting cycles were applied; drying by means of evaporation and wetting using the application of water droplets. The matric suction, vertical and radial displacement, and mass change of the specimens were all monitored continuously during the cycles. The equipment is the first to provide natural drying, unconstrained shrinkage or swelling with continuous measurements of volume, suction and water content in a way that could readily be used in engineering practice. The results indicated that drying-wetting cycles resulted in accumulated irreversible shrinkage. However, the amount of shrinkage decayed very significantly as the number of cycles increased, and the behaviour became almost repeatable after the third cycle. It was also observed that the positions of soil water retention curves (SWRC) under wetting-drying cycles shift downwards with the increasing number of cycles; the larger the number of cycles, the smaller the difference between the curves and after 2 or 3 cycles, the difference became steady. The shape of the curves changed very obviously under the first three wetting-drying cycles but less significantly after this.

Keywords:

water retention curves; shrinkage; volume change; matric suction; clay; drying; wetting

¹Corresponding Author. Email: d.g.toll@durham.ac.uk

1. Introduction

Unsaturated compacted soils used for embankments are inevitably subjected to wetting and drying cycles due to seasonal variations, especially during extreme weather such as intense rainfall and longer drier periods. Strength and volume characteristics changes need to be investigated and accounted for in the design of soil structures. The key driving parameter associated with volume and water content changes is the negative pore-water pressure (or suction) (Fleureau et al, 2002).

A key piece of information for the design of soil structures is the soil water retention curve (SWRC), describing the relationship between suction and water content (or degree of saturation) of a soil. This paper describes a technique for determination of soil water retention curves using high capacity tensiometers. The apparatus described can provide continuous measurements of volume, suction and water content in a way that could readily be used in engineering practice, due to its simplicity and speed of testing.

The benefit of using high capacity tensiometers is that suction measurements can be carried out with the sample maintained at atmospheric air pressure. Previously, the only alternative method for direct measurement of suction was to use the axis translation technique (where the sample air pressure is elevated so that the pore water pressure becomes positive). This prevents cavitation from taking place in soil samples as the pore water pressure is always maintained above absolute pressure (gauge pressure of -100 kPa). In this case, desaturation is controlled entirely by air entry from the sample boundaries. However, a soil that dries in a natural condition in the field will be subject to negative pore water pressures, when cavitation might be induced in larger pores within the soil. The water content or degree of saturation could therefore be different, depending on whether cavitation could take place, or not. Being able to measure the negative pressure directly using a high suction tensiometer allows measurements to be obtained on soils at atmospheric air pressure, replicating the natural state, with the true arrangement of water that would exist in that state.

Cunningham (2000), Boso et al. (2003), Toker et al. (2004), Teixeira and Marinho (2006) and Lourenco et al (2011a) have reported the determination of SWRCs with high-suction tensiometers to measure suction and an electronic balance to record water content. The use of high capacity tensiometers for determination of soil water retention curves provides a significant improvement in terms of the time required for testing (Toll et al, 2013), in some cases reducing the time to days rather than weeks or months.

The tensiometer technique can be used in two ways (i) discrete drying, where the specimen is sealed after a period of drying to allow equilibration of suction and water content within the specimen before measuring suction or (ii) continuous drying, where pauses for equalisation are not imposed (Lourenco et al, 2011a). However, the rate of drying may be slowed down (by partial enclosure) to ensure that potential non-homogeneity within the specimen is limited.

Boso et al. (2003) presented a comparison between SWRCs obtained by discrete and continuous drying for samples of reconstituted clayey silt. The evaporation rate during continuous drying

was slowed down by wrapping the sample in a porous geotextile. The results revealed no differences between the SWRCs using the two procedures. Cunningham (2000) investigated the influence of the evaporation rate on the measured SWRC for continuously dried samples of reconstituted silty clay. Similar results were obtained, suggesting that the evaporation rate had little or no influence on the resulting SWRC. Likewise, Lourenco et al (2011a) found that the SWRCs obtained by the continuous drying procedure were consistent with the SWRCs obtained by discrete drying. This suggests that suction gradients, if they exist during continuous drying, have limited impact on the measurements and the technique can be used for determination of SWRCs.

It is tempting to benchmark a new technique, like the tensiometer technique, against other established techniques such as pressure plate and filter paper techniques. When this has been done, discrepancies have been found. For instance, Cunningham (2000) reported a comparison between the SWRCs obtained by continuous drying and the filter paper method; Teixeira and Marinho (2006) compared the SWRC obtained by discrete drying with the pressure plate and by the filter paper method. Tarantino et al (2011) compared the SWRC from discrete drying with pressure plate tests and osmotic methods. The difference in water content at the same suction between these different methods of determining SWRCs tended to be larger than 5%.

A larger comparison of SWRCs measured in different ways has been reported by Toll et al (2015). This found that the differences between tensiometer measurements, pressure plate tests and filter paper measurements could be explained by differences in the volumetric paths followed. These differences in shrinkages paths (imposed by the different contact arrangements between the specimen and what it rests on) can reduce the radial shrinkage and result in different desaturation conditions. Therefore, it has to be appreciated that tensiometer techniques will not necessarily be comparable with pressure plate tests. It could be argued that the tensiometer technique, where the specimen often rests on a smooth plastic base and has less restraint from shrinkage, may give “better” results than the pressure plate tests, where adhesion between the specimen and the ceramic provides a restraint to shrinkage.

There have been previous studies of the influence of repeated wetting and drying cycles on the matric suction and volume changes of clayey soils. Alonso et al (2005) investigated the effect of applying wetting–drying suction cycles (4–130MPa) on an expansive bentonite–sand (80/20) compacted mixture, by means of vapour equilibrium technique in an oedometer cell. They observed that samples experienced a progressive shrinkage as the suction cycles accumulated. Landfill liner soils with similar shrinkage behaviour were investigated by Yesiller et al (2000) who considered the changes with cycles to be caused by decreases in the size of the pore spaces. They observed increased suction, which was approximately 5000 kPa in the first and third drying cycles and 5700 kPa in the second cycle, when investigated by psychrometers in large-scale samples of compacted soils subjected to three wet–dry cycles (0–6000kPa). McCartney (2010) presented an experimental investigation of transient movement of water in unsaturated layers underlain by a geocomposite drainage layer during cycles of infiltration and evaporation. Tensiometer measurements showed a small decrease in suction as the wetting front passed their locations in successive cycles. However, Nowamooz and Masrouri (2010) observed a cumulative swelling strain for dense soils, while a shrinkage accumulation was observed for loose samples

when subjected to suction cycles. Dif and Bluemel (1991) investigated the fatigue phenomenon of an expansive soil due to cyclic drying and wetting using a modified oedometer and found that the net decrease in volume after each drying and wetting cycle for the soil tested became smaller until an equilibrium was reached. Harrison and Blight (2000) and Oloo and Fredlund (1995) employed suction measuring devices to study variations of matric suction in-situ and in pavement layers respectively. Gong et al (2006), Wang et al (2007) and Zhang and Chen (2010) investigated the variation of matric suction, deformation and strength of unsaturated clays subjected to repeated drying and wetting cycles with different clays and types of apparatus.

The above-mentioned studies showed different results about suction and volume change of compacted soils subjected to wetting and drying cycles, some even contrary. Furthermore, few tests have measured suctions and volume changes simultaneously and continuously, so limited results have been reported with respect to details on differences of matric suction and volume changes between repeated wetting and drying cycles. In addition, tests of drying and wetting cycles in the low suction range (0-1500kPa) are rarely reported.

This study was conducted to investigate the influence of repeated wetting and drying cycles on matric suction and volume changes of a glacial till soil used in the construction of an experimental embankment within the BIONICS project, funded by the Engineering and Physical Sciences Research Council, UK (Hughes et al, 2009). Soil specimens were placed on a new apparatus in direct contact with a high suction tensiometer, and the repeated drying and wetting cycles were applied by means of evaporation (for drying) and water droplets (for wetting). The matric suction, vertical and radial displacement, mass change (water content change) of specimens were all continuously monitored during the cycles and then analysed.

2. Experimental program

2.1 Tested Material

The soil used in this study was a glacial till (Durham Lower Glacial Till) obtained from fill material used in the experimental embankment of the BIONICS project in North East England (Toll et al, 2012). The material was prepared by sieving through a 2.8mm sieve to remove the larger particles to reduce the variation in properties (Mendes, 2011). The sieved material was composed of 30% sand, 35% silt and 35% clay, i.e. a sandy clay soil. The Liquid Limit was 43.3% and the Plastic Limit was 23.7%, resulting in a Plasticity Index of 19.6 and a Liquidity Index of -0.05 (Noguchi et al, 2012). The optimum water content and maximum dry density for the Proctor 2.5kg compaction test were $w_{opt} = 15\%$ and $\gamma_{d\ max} = 1.719\text{ Mg/m}^3$ (Mendes, 2011).

2.2 Experimental apparatus

The experimental apparatus was modified from setups designed by Lourenco (2008) and Noguchi et al (2012) to allow continuous measurements of water content, suction and volume change. The apparatus was made up of a PVC frame and a bottom plate, with an adjustable height PVC support plate to hold the sample (shown in

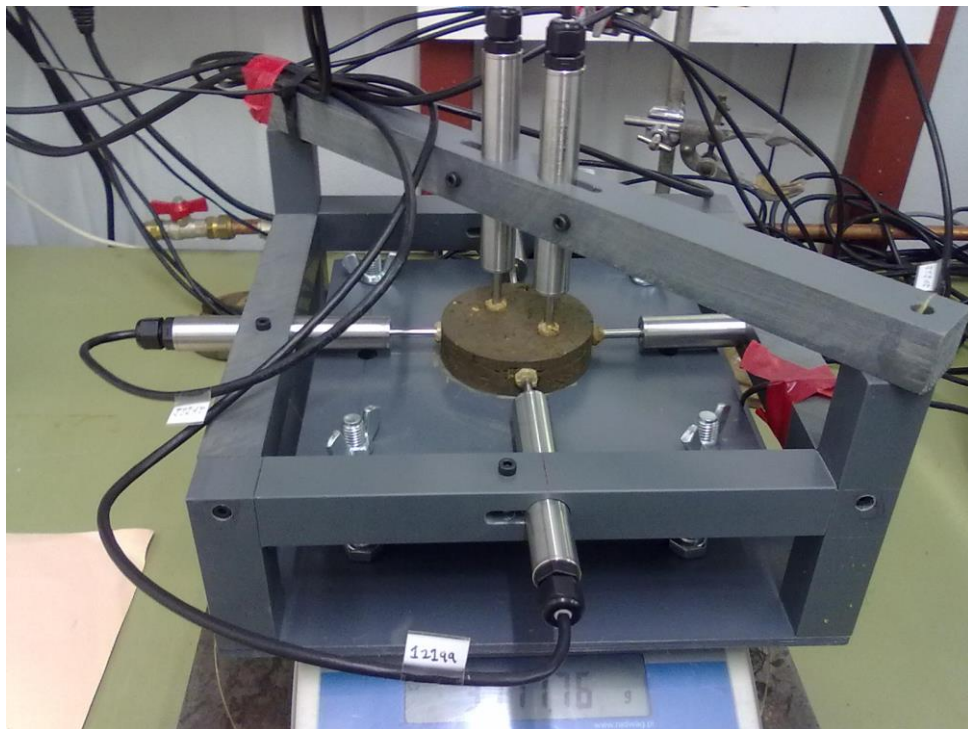
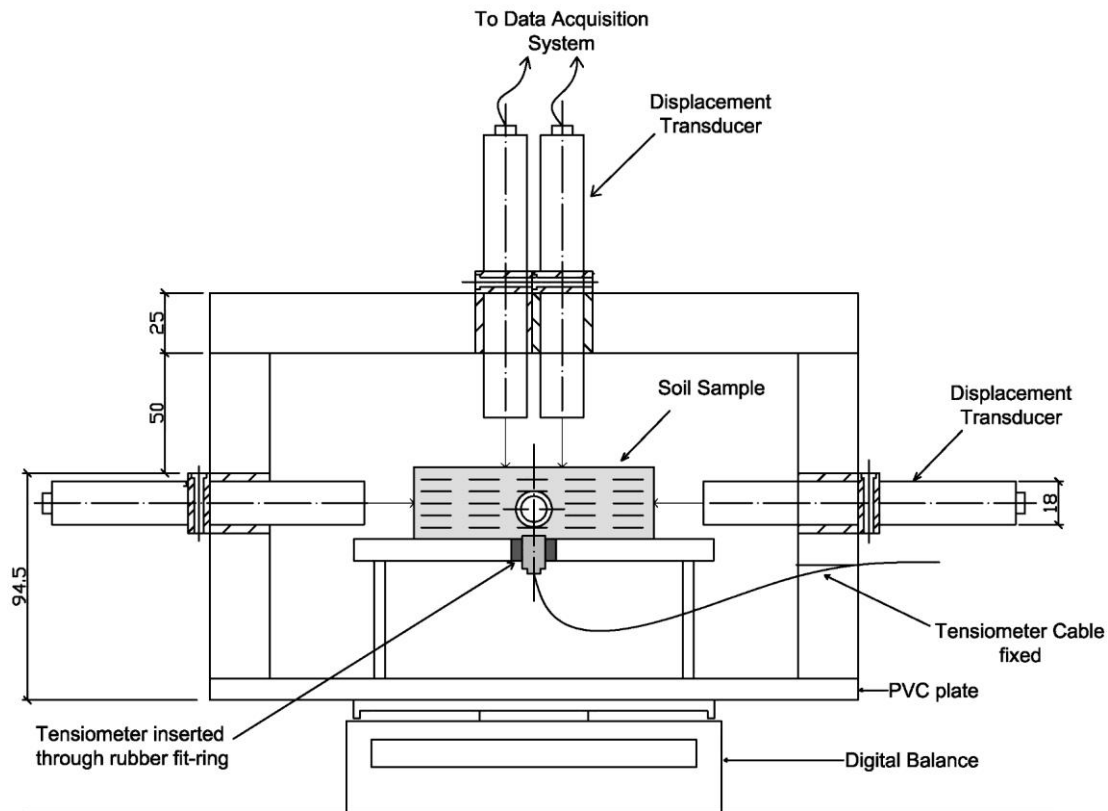


Figure 1 and

Figure 2). PVC material was used to limit the overall weight of the apparatus as it was placed on an electronic balance to determine the change in sample weight and hence water content (Lourenco et al, 2011a).

A key development was the ability to measure volume change continuously, to support the other measurements of suction and water content. Fredlund (2015) advocated the measurement of

volume (in this case, the shrinkage curve for the first drying) on a separate specimen to provide the essential information on volume change to allow calculation of degree of saturation or volumetric water content. However, it is clearly preferable to measure the volume change on the same specimen for which suction and mass changes are being observed. Toll et al (2015) noted that volume change measurements are essential, as different volumetric paths are followed in different tests for determining water retention curves (e.g. pressure plate and tensiometer techniques). Therefore, water retention curves should never be measured without the accompanying volumetric response.

While volume changes have been measured previously, as part of SWRC determination, these have typically been done using point measurements using Vernier callipers to measure sample dimensions (e.g. Al-Mahbashi et al, 2016; Al Haj and Standing, 2016). Another technique is to use immersion in Kerdane (Péron et al, 2007), but this allows only one measurement per specimen. Neither technique provides a continuous record of volume change. While volume measurements in an oedometer (e.g. Dif and Bluemel, 1991; Alonso et al, 2005) or in the Fredlund SWCC cell (e.g. Al-Mahbashi et al, 2016) can provide continuous measurement of swelling, through measuring the vertical change in height under one-dimensional constrained conditions, they are not reliable for shrinkage, where the specimen can shrink away from the fixed cell wall. Volume measurements have been made in a double wall triaxial cell (e.g. Estabragh and Javadi, 2014), but this usually requires suction control to be applied by axis translation. The system proposed by Lourenço et al (2011b) does allow natural drying to be imposed in a double cell triaxial system, but this is still much slower than natural drying in air in the laboratory environment. Therefore the equipment, described here is the first to provide natural drying, unconstrained shrinkage or swelling with continuous measurements of volume, suction and water content in a way that could readily be used in engineering practice.

For volume change measurements, four displacement transducers were installed through the four outside beams of the frame to measure radial displacement of the specimen and two more displacement transducers were fitted through the upper beam to measure axial displacement (change in height). Volume change of the specimen could then be calculated from the radial and axial deformations.

A high suction tensiometer (Lourenco et al, 2006; Toll et al, 2013) was used to measure suction. These devices have been used for direct measurement of suction as large as 2000kPa, although the range was limited to 1200kPa for these tests reported here. The tensiometer was fitted through a hole in the support plate, with a tight fitting rubber O-ring to secure it in place. The support plate could be adjusted in height above the base to ensure the displacement transducers were positioned at the mid-height of the sample. All transducers were connected to a real-time data acquisition system (Toll, 1999).

All the cables of the transducers and the tensiometer were fixed and supported by three retort stands to minimize the influence of cable stiffness on the mass measurement (Toker et al. 2004, Lourenco, 2008). The influence of cables on mass measurement was observed by measuring the mass change of the whole apparatus without a specimen for 11 hours and the results showed that mass change was less than 0.25g.

The experimental apparatus was placed in a laboratory in which the temperature was controlled between 22.3° and 23.3° C and the recorded relative humidity fluctuated from 46.5% to 51.1% during the tests.

2.3 Test procedure

The sieved soil was oven-dried for 24 hours then wetted to 20% water content. This was wet of optimum and nearly equal to that of soil compacted in the experimental embankment in the field (Hughes et al, 2009). The wetted soil was sealed in plastic bags for more than seven days of hydration to promote uniform water absorption prior to compaction; large soil clods were also broken down into smaller ones (maximum equivalent diameter <10 mm). The soil was compacted by a drop-hammer compaction machine using a modified version of the standard Proctor test (BS light compaction, BS 1377-4, 1990) (using a 2.5kg hammer falling through 300mm with 27 blows per layer on 6 layers having a thickness of 33mm) to form one large sample of 200mm height and 100mm diameter. This sample was subsequently sliced into 5 sub-samples of 40mm high and 100mm diameter. Before testing, these sub-samples were trimmed to specimens with 20mm thickness and 75mm diameter. The water content and densities were determined as shown in Table 1. The prepared specimen was quickly placed on the support plate, through which the tensiometer was inserted by gently pushing to make an intimate contact between the specimen and the probe.

During drying paths, the specimen was dried to atmosphere allowing evaporation from top and side surfaces. A water content change from about 20% to 15% was obtained in about 12 hours. The specimens could not be dried to a lower water content as that would induce cavitation of the tensiometers, so a drying path was ended when the suction increased close to the limit of the tensiometers (~1500 kPa).

Wetting paths were accomplished by gently injecting a calculated mass of distilled water using a syringe on to the specimen surface. The water was applied in the evening and the specimen was then covered with a wetted sponge and plastic membrane and left overnight, so the specimen was evenly moisturized and drying was limited. Next morning, the drying path started again and the wetting path began in the evening. Repeated wetting and drying cycles were carried out as described above. After completion of the test, the specimens were oven-dried, which allowed calculation of their water content.

3. Results and discussion

Six different specimens were tested with the same initial gravimetric water contents (19.7 ± 0.7) (Table 1). Tests 1-4 followed a single drying path after compaction (Test 3 was unsuccessful), while Test 5 and Test 6 were studied under more wetting-drying cycles.

The mass (water content) changes monitored by the electronic balance for Test 5 are presented in Figure 3 to illustrate the procedure followed. In this test, the water content (calculated according to mass changes) was controlled to almost the same value at the end of every drying path except for the last cycle, where the drying was deliberately extended to the limit of the tensiometer's

suction range. Wetting cycles comprise the “wetting” i.e. adding drops of water and the subsequent “moisturizing” i.e. equalisation overnight. Note that the total mass decreases slowly with time during “moisturizing” as the specimens were not completely sealed to prevent evaporation from the specimens. The apparent sudden drop before drying was due to the careful removal by a pair of tweezers of the sponges that were applied during “moisturizing”.

3.1 Water content changes

The changes in water content of the specimen with elapsed time for the first drying path of 5 tests are as shown in

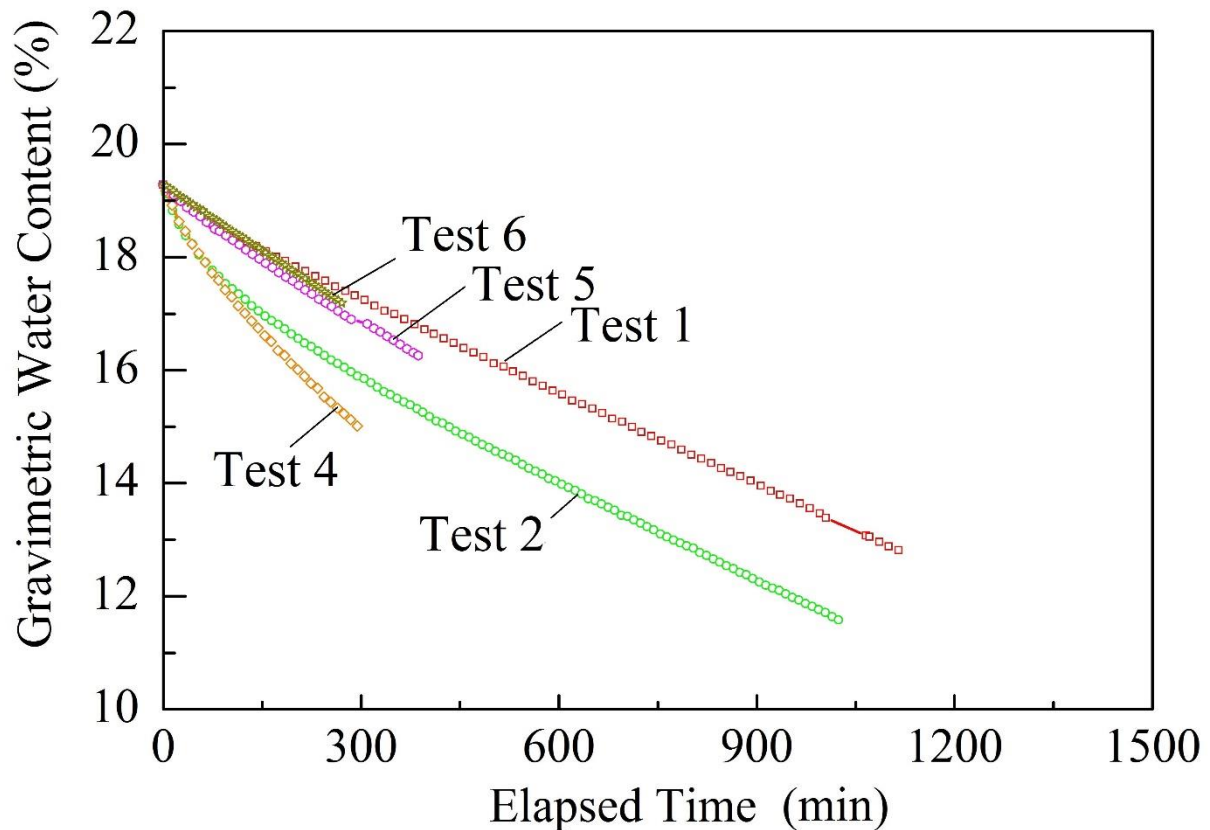


Figure 4. The water contents reduced with elapsed time nearly in a linear relationship which indicated that the dehydration rate was almost constant (as observed by Lourenco et al, 2011a). The dehydration rates of Test 1, 5 and 6 were similar to each other, and those of Test 2 and Test 4 were similar to each other. This difference between the two groups of tests could be due to differences in density (Table 1); Tests 2 and 4 were obtained from the upperpart of the sample when compacted with a density of 2.058 Mg/m^3 ; Tests 5 and 6 were obtained from the lower layer and had lower densities of $2.018\text{-}2.036 \text{ Mg/m}^3$.

The drying curves for all cycles of Test 5 and Test 6 are shown in

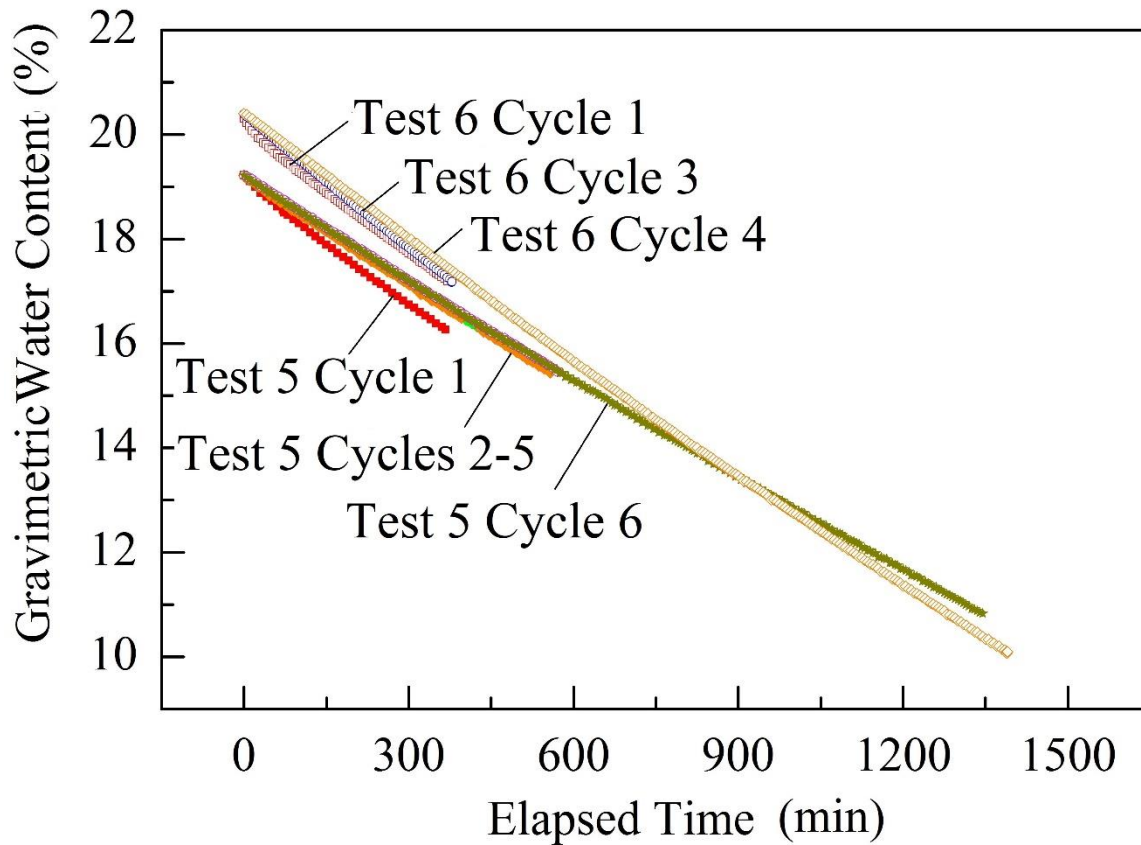


Figure 5. The dehydration rate along the drying paths showed a small decrease as the wetting-drying cycles increased. However, all were close to linear. Test 6 showed very similar results to Test 5. The results demonstrate that the compacted BIONICS soil had a steady dehydration rate of 0.008%/min when subjected to wetting-drying cycles when the temperature and humidity were near constant.

3.2 Volume change under drying-wetting cycles

The volume changes of 5 specimens during drying paths are presented in

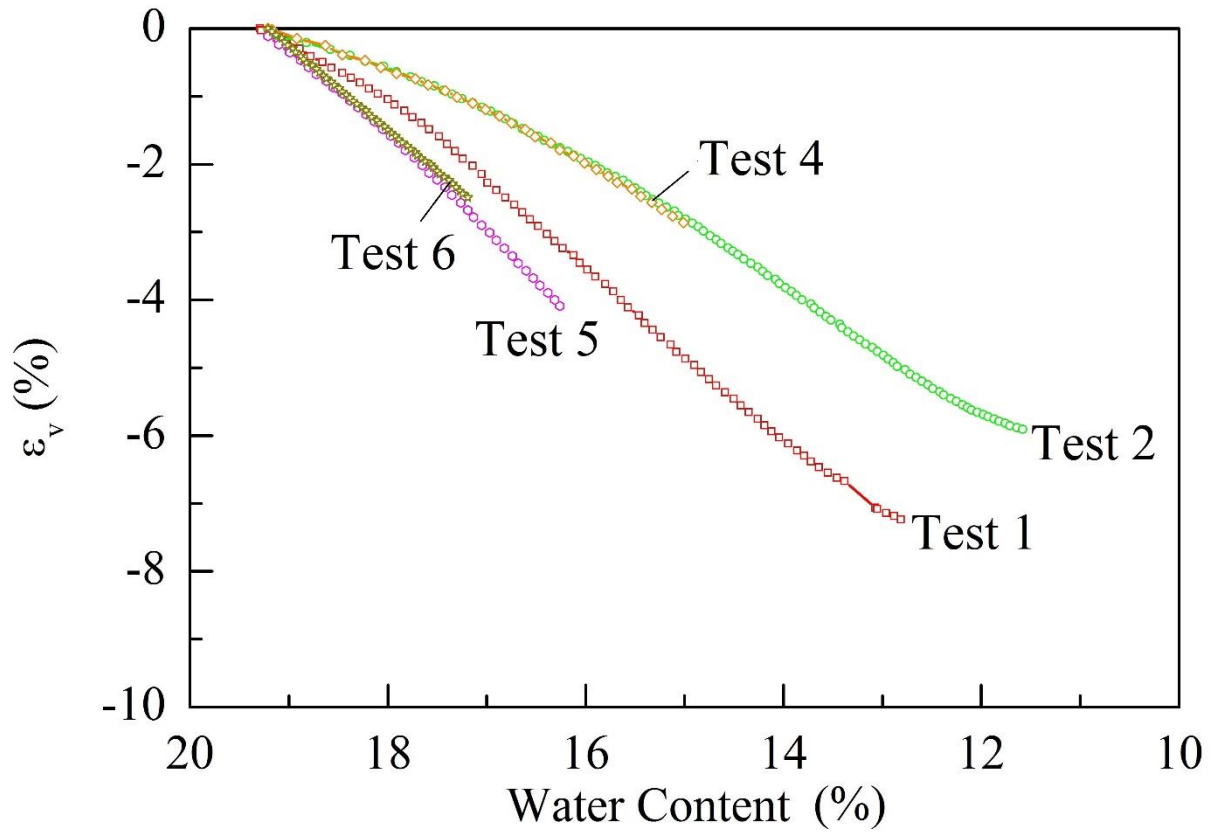


Figure 6 which shows that different specimens with the same initial water content had different shrinkage rates. This may be related to the small density differences among the specimens. The denser samples used in Tests 2 and 4 (density of 2.058 Mg/m³) show less volume change compared to the less dense samples in Tests 5 and 6 (densities of 2.018-2.036 Mg/m³).

The specimen in Test 5 was wetted and dried to the same water content in each wetting-drying cycle, except the final cycle 4 when drying was extended. The specimen showed shrinkage during the drying paths and swelling on the wetting paths

(

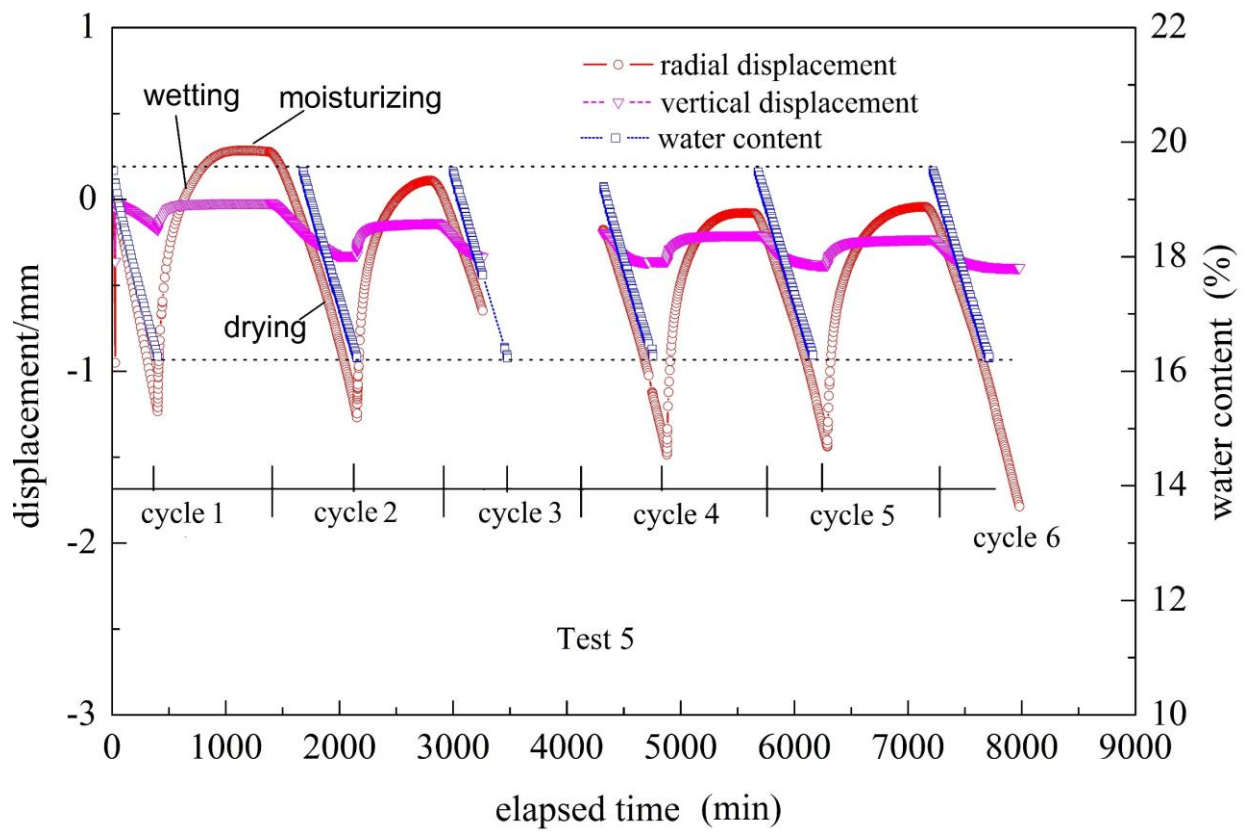


Figure 7). However, the total volumetric change for Test 5 at the wettest point (nearly saturated) showed overall swelling for the first wetting path (as can be seen particularly strongly by the increase in radial displacements) and then subsequently overall shrinkage (relative to the initial state) after drying and wetting as indicated in

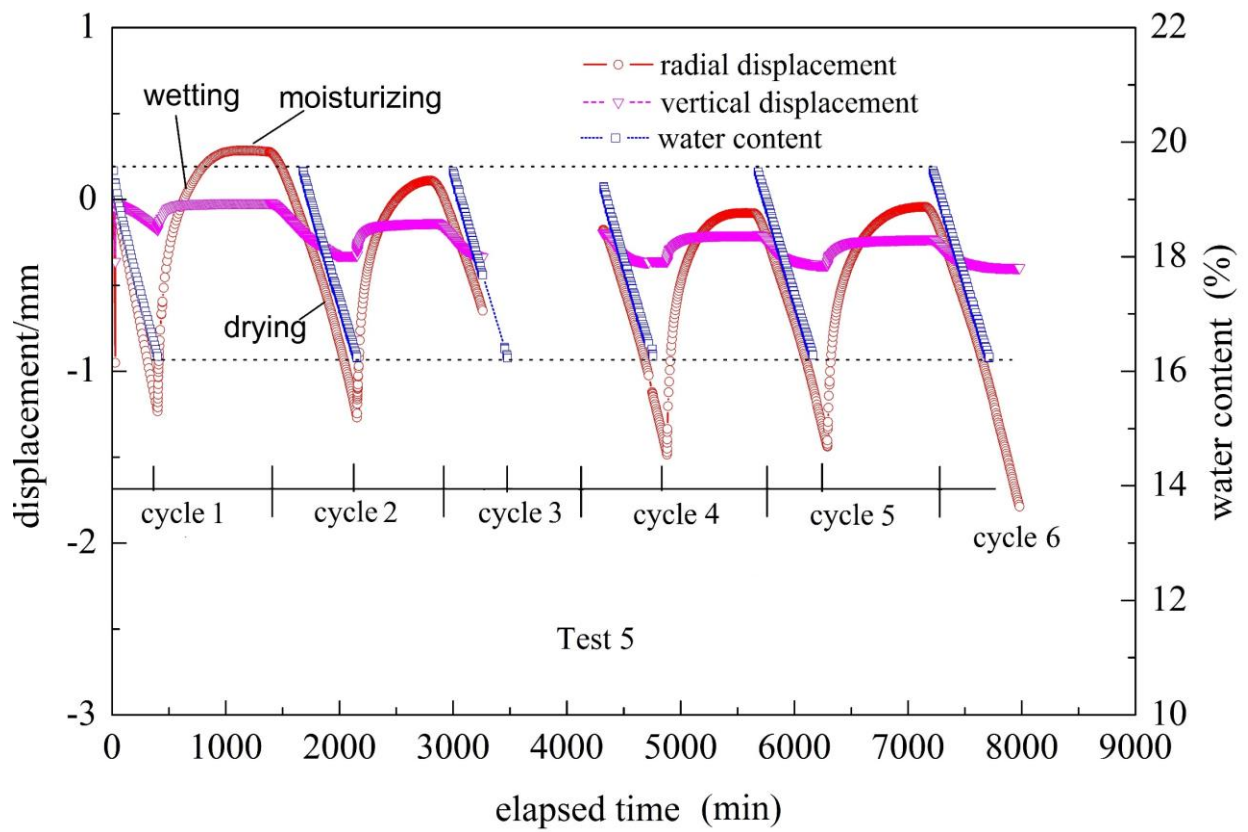
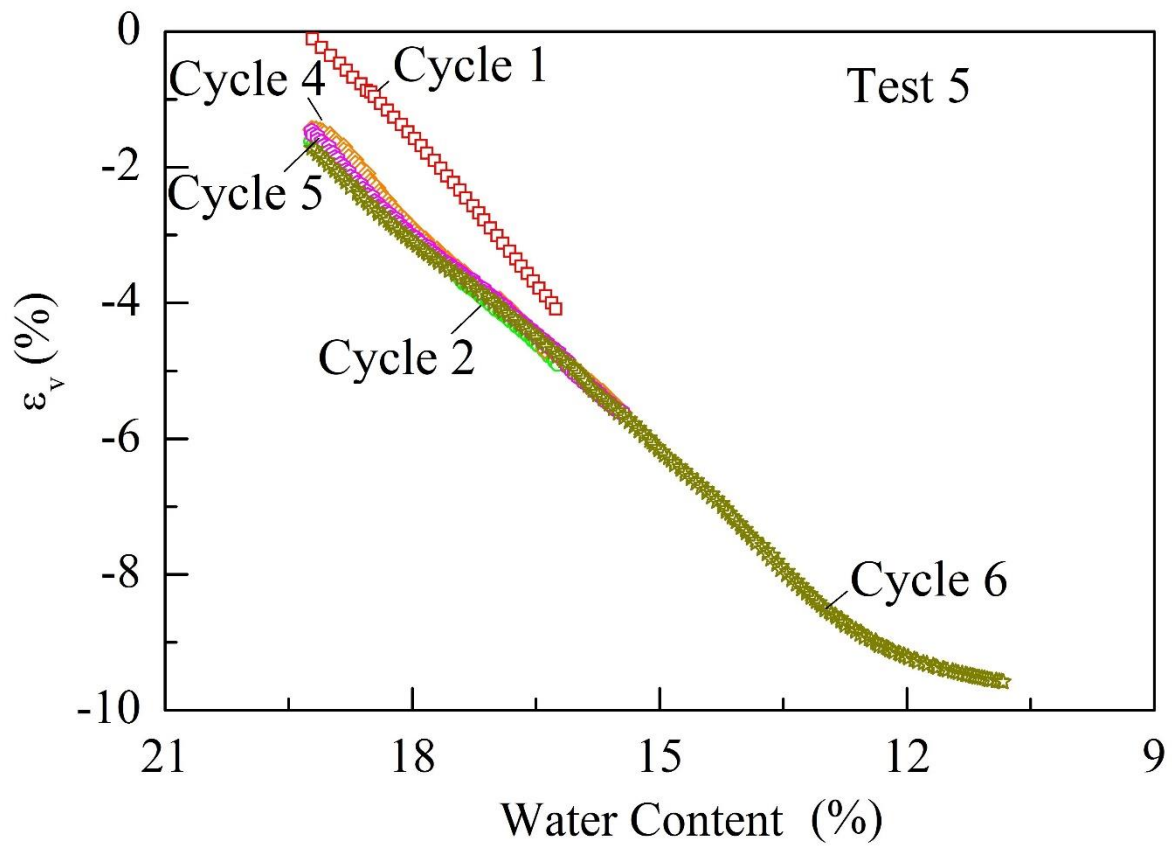


Figure 7. The maximum and the minimum points of displacement had an obvious decline with the increasing number of cycles, meaning that accumulated irreversible shrinkage was taking place due to the wetting-drying cycles. However, by the 4th and 5th cycle the volumetric

response was very similar, indicating almost elastic behaviour



(
Figure 8). This is similar to the behaviour observed by Alonso et al (2005) and Airò Farulla et al (2010).

For the cycles of Test 5 and Test 6 with same initial water content (shown in

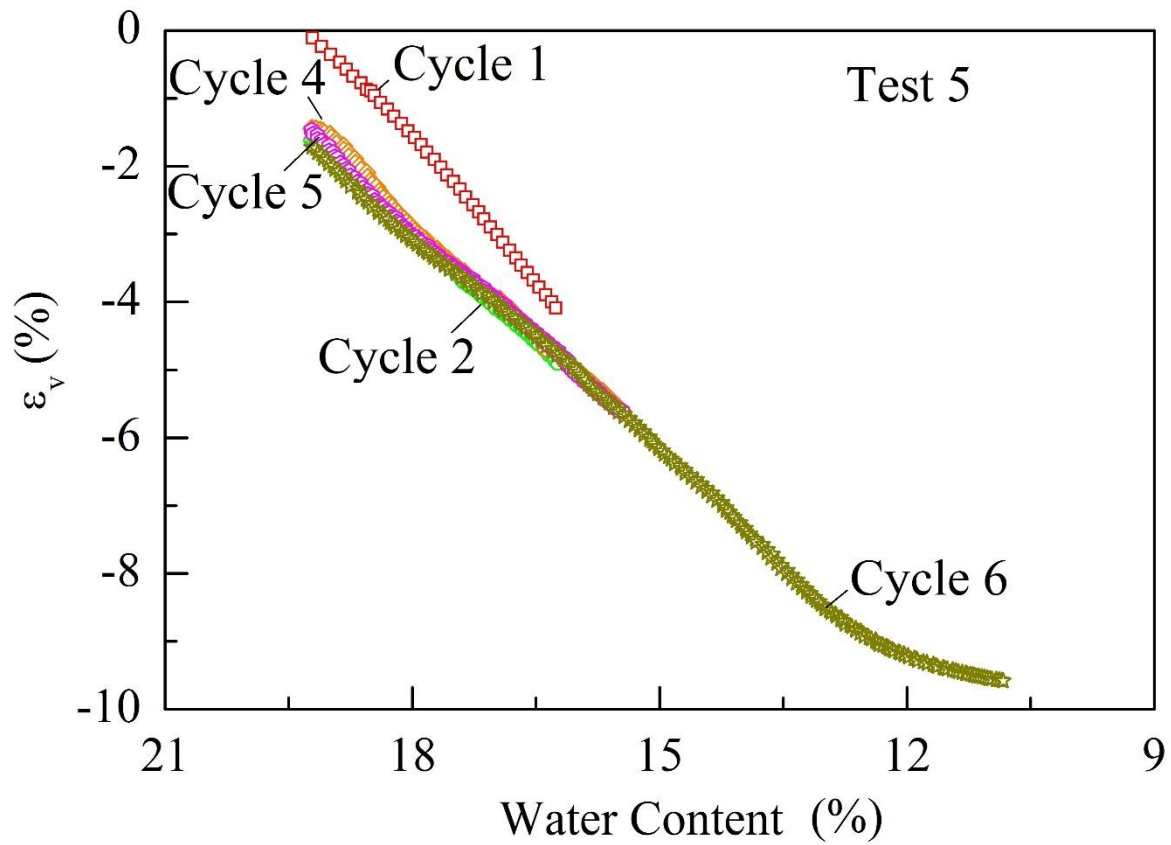


Figure 8 and

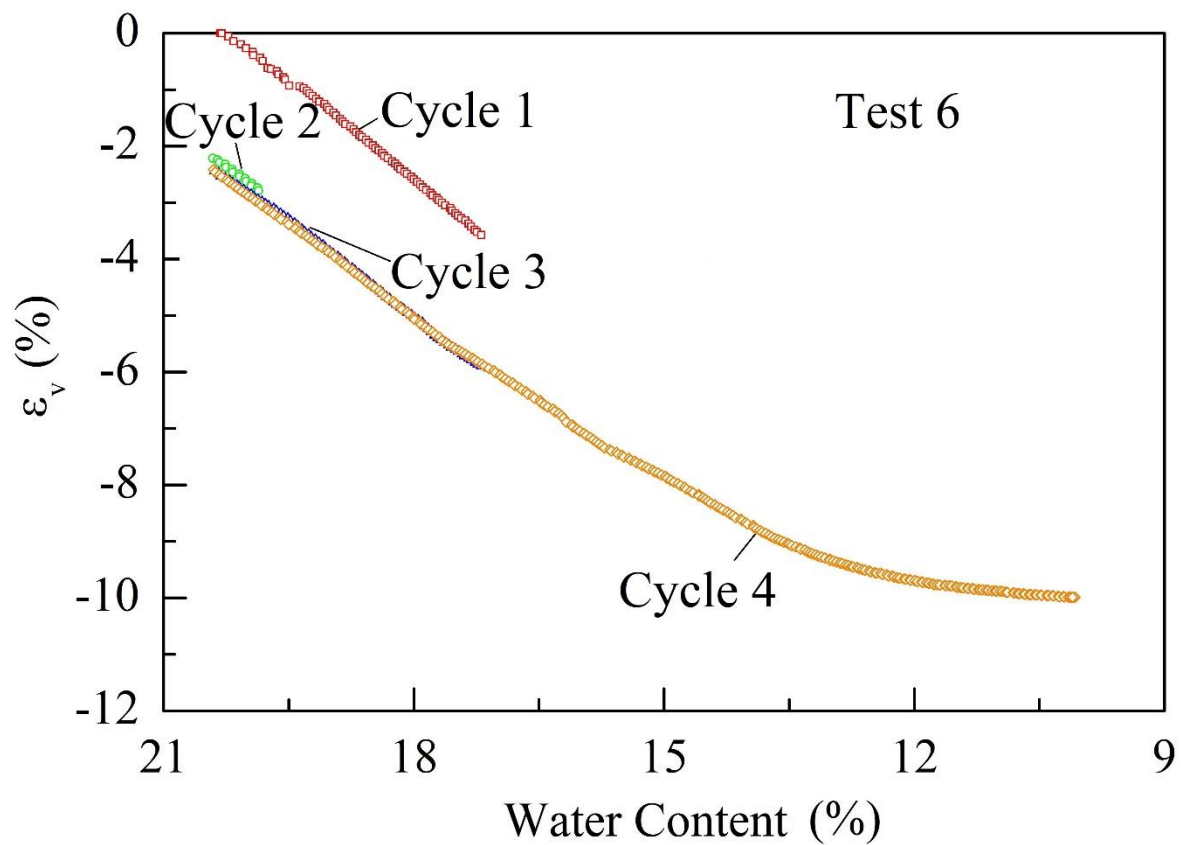


Figure 9), the shrinkage rate decayed very clearly with the number of cycles, and the shrinkage

rate was nearly the same by the third cycle. It was also observed that the shrinkage rate had a turning point at a water content of about 13% for Test 5 and Test 6. When the water content was higher than 13%, the volume of specimen shrank nearly linearly with the water content, and when the water content was lower than 13%, the shrinkage rate decreased more slowly with the water content (indicating a shrinkage limit).

3.3 Matric suction change under drying-wetting cycles

Specimens in Test 5 and Test 6 were tested under similar drying-wetting cycles. For Test 5, the drying paths were started and then ended in the same water content until the last cycle. Matric suction corresponding to the lowest water content reduced sharply with the number of the cycles as shown in Figure 10.

The SWRC curves in terms of gravimetric water content for Test 5 and Test 6 are shown in

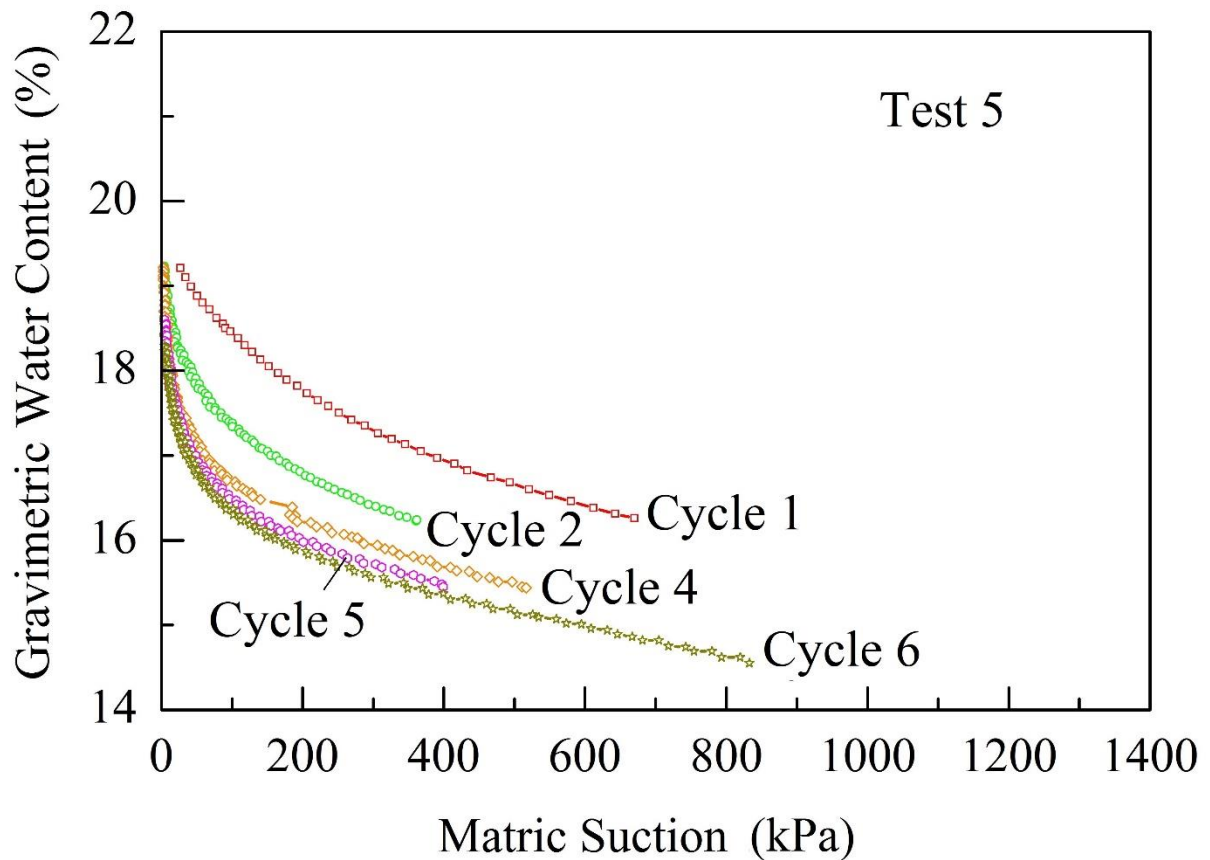
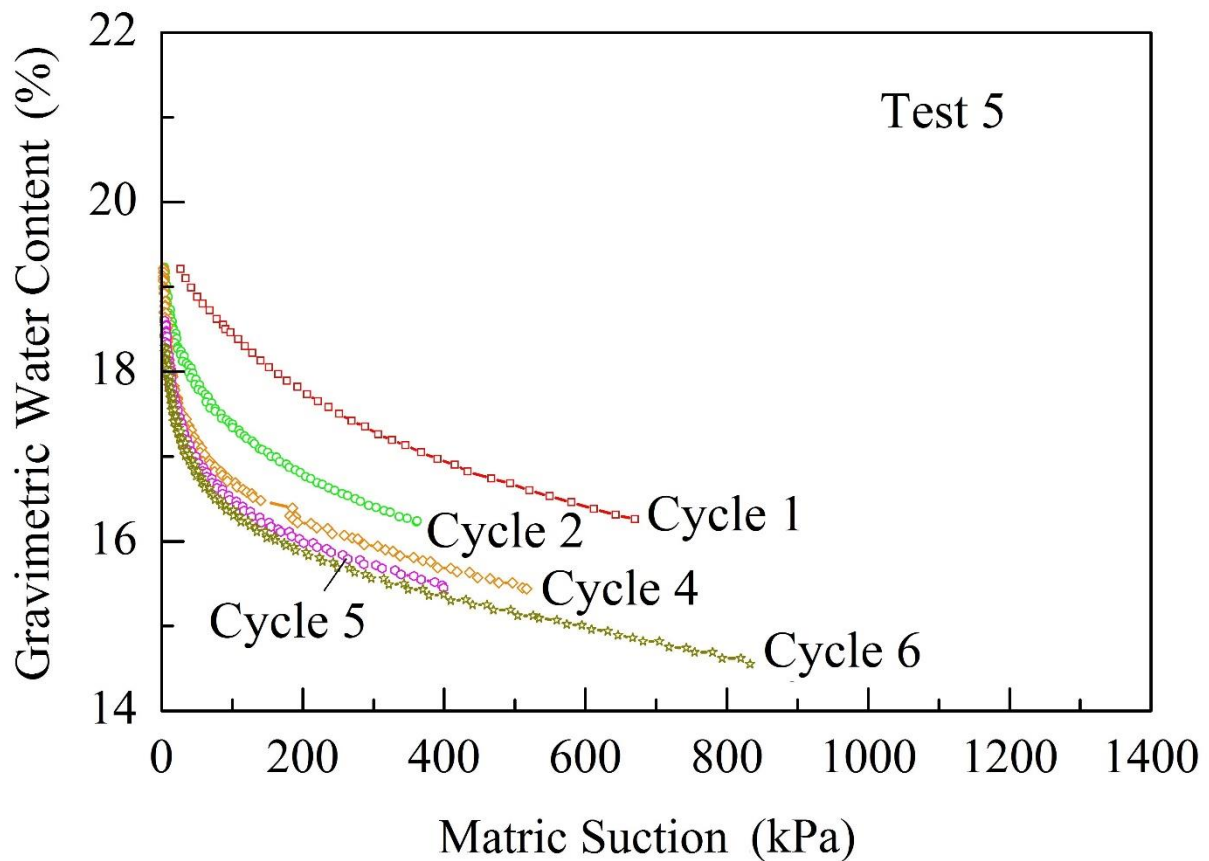


Figure 11 and Figure 12 respectively. It can be seen that the positions of SWRC curves shift downwards with increasing cycles, and for the latter cycles, the difference between the curves becomes smaller. For Test 5, when dried to the same water content of 16.3% under 6 cycles



(Figure 11), the corresponding matric suction decreased from 649kPa (cycle 1) to 334kPa (cycle 2), 182kPa (cycle 4), 128kPa (cycle 5), 102kPa (cycle 6) (unfortunately data was lost for cycle 3). These latter values for cycle 5 and 6 are equivalent to about 20% of the suction change recorded in the first cycle. For Test 6 (Figure 12), when dried to the same water content of 17.2%, the related matric suctions fell from 405kPa (cycle 1) to 278kPa (cycle 3), 243kPa (cycle 4) (data was lost for cycle 2).

The ability to continuously monitor volume change and water content with the Durham SWRC apparatus provides the opportunity to have continuous observations of degree of saturation during cycles of drying and wetting. The relationships between matric suction and degree of saturation for Test 5 and Test 6 can be seen in

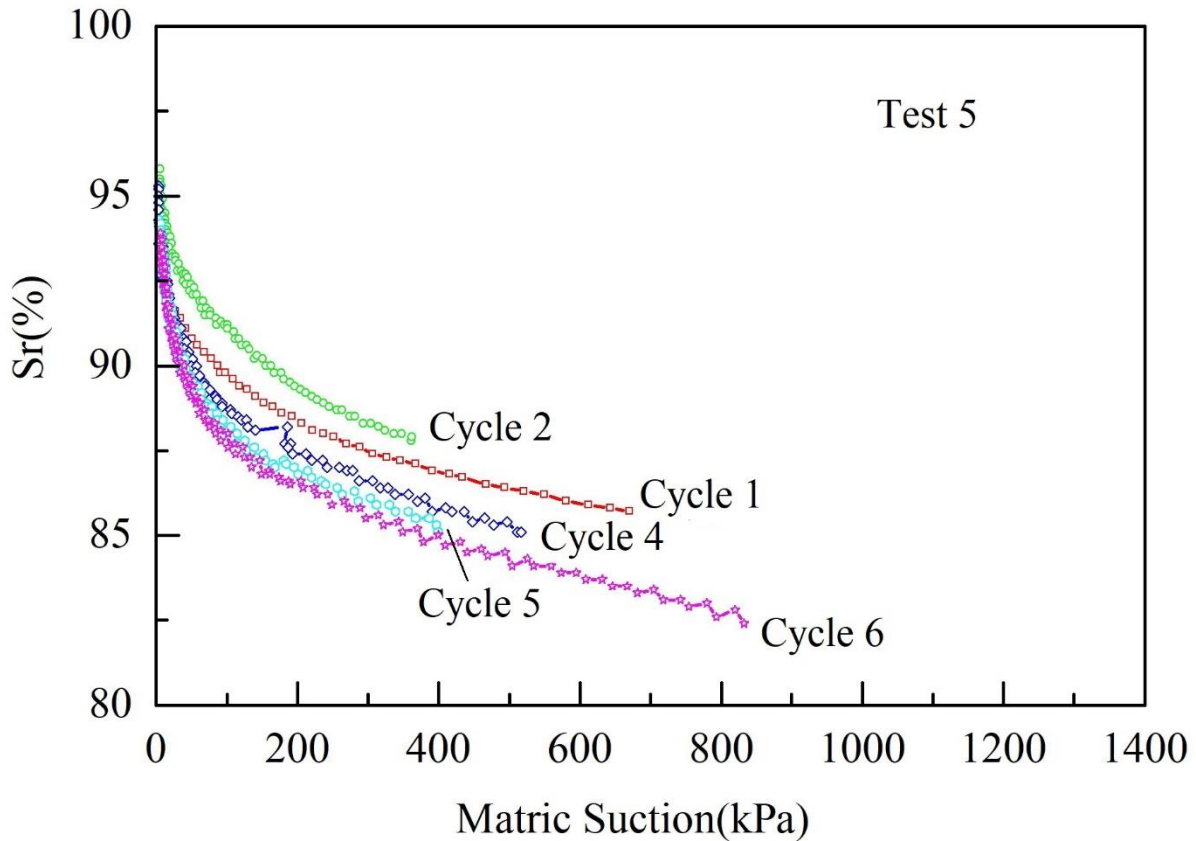


Figure 13 and Figure 14 respectively. It can be seen that after wetting in the first cycle, the degree of saturation increases closer to 100% in both tests. For subsequent cycles, as for the SWRC curves, the position of the curves shift downwards with increasing cycles, and the difference between the curves gets smaller.

Airò Farulla and Jommi (2005) explain the fabric changes that result from the volume changes induced by wetting and drying. The pore size distribution shifts and changes as shrinkage takes place, producing significant fabric changes in the first wetting and drying cycle. They suggest that the irrecoverable void ratio reduction is likely to be associated with the loss of the inter-aggregate pore system (macropores). In contrast, Pires (2008) observed that for compacted soils of mixtures of clay and sand, inter-aggregate pores larger than $500\mu\text{m}$ suffered a major increase after wetting-drying cycles. Burton (2015) demonstrated that a bimodal microstructure is not recovered on drying from a saturated state for compacted high plasticity clay.

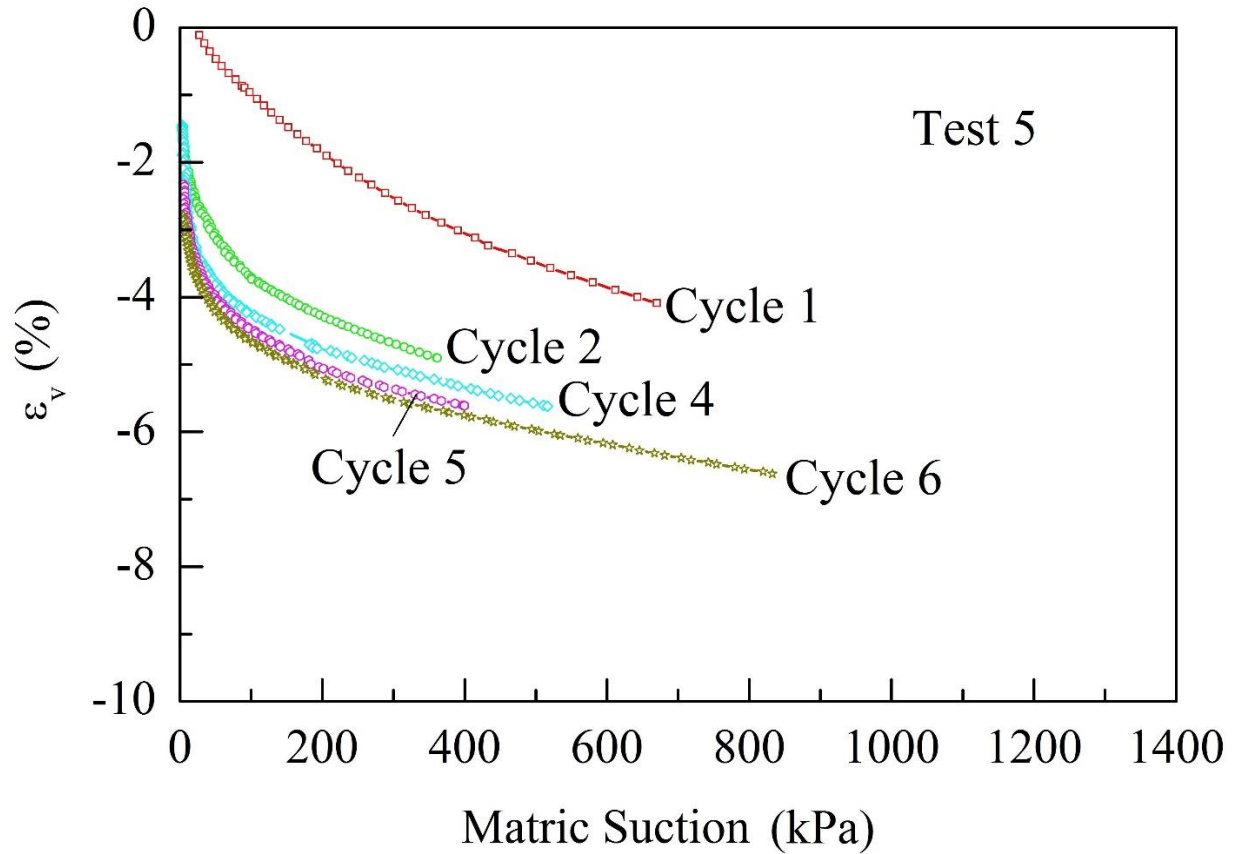
The shifts in the soil water retention curves suggest that the irrecoverable shrinkage induced in the first cycles means a loss of macropores, resulting in the same amount of water producing a lower suction. This would support the observations of Airò Farulla and Jommi (2005). These shifts in the SWRCs mean that, even for the same specimen, the SWRC curves under several wetting-drying cycles cannot be simulated by a single equation such as the equation proposed by Fredlund and Xing (1994). However, after three wetting-drying cycles, the shape and location of the SWRC curves does not change significantly, as noted by Alonso et al (2005).

Comparing these two specimens from the same compacted sample, although the initial water content, density and the testing method were very similar, the SWRC curves showed distinct

differences. This is likely to originate from variations in the soil fabric, demonstrating the sensitivity of SWRCs to such factors.

3.4 Relationship between volume change and matric suction

Volume changes with matric suction in cycles of drying and wetting are presented in



Figure

15

and

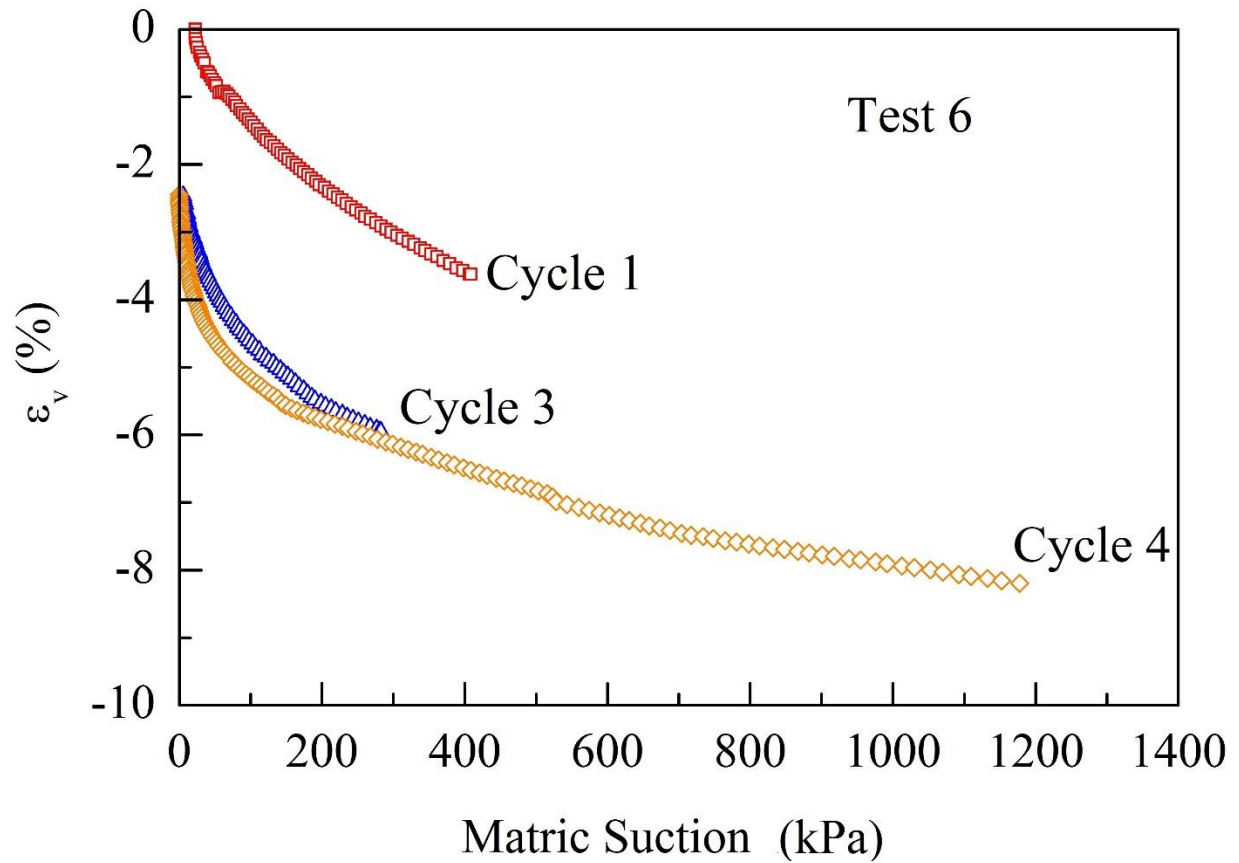


Figure 16 for Test 5 and Test 6. The relationship between volume change and matric suction was very similar to that between volume change and water content as described in 3.3. The two specimens both experienced a progressive shrinkage as the suction cycles accumulated, but most shrinkage took place in the early cycles.

The differences in strain in the radial and vertical directions are shown in

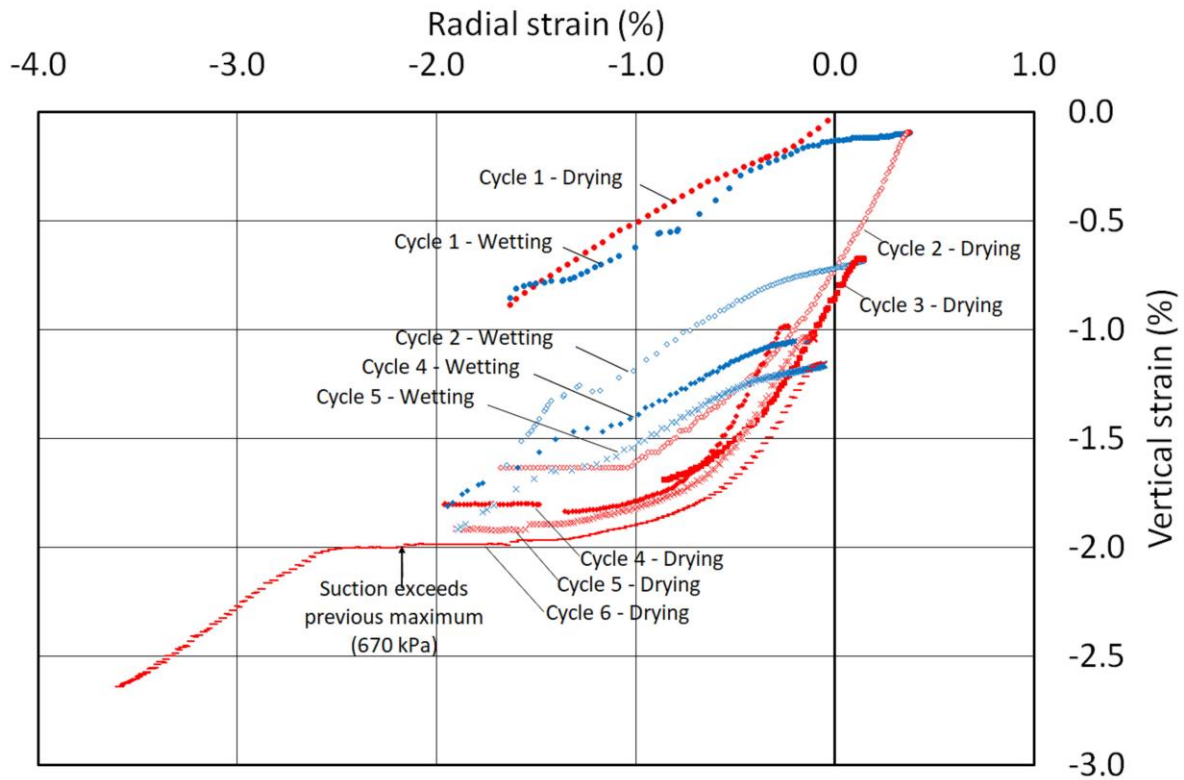


Figure 17 for the drying and wetting cycles of Test 5. It can be seen for the first drying (Cycle 1) that the strain path is approximately linear, although the response is anisotropic, as the vertical strain is approximately half of the radial strain. On the first wetting, the response over much of the cycle is close to elastic, as the wetting path follows a similar trend to the initial drying path. However, the radial strain continues to increase beyond the initial state resulting in overall radial swelling (0.4%) of the sample, whereas the vertical strain shows an overall shrinkage of 0.1%.

On the second drying (Cycle 2) the response is very different. Initially the vertical strain increases more than the radial strain, then in the later part the vertical strain becomes almost constant while the radial strain continues to increase, resulting in a curved path. The wetting path for Cycle 2 also shows the vertical strains reducing more initially and the radial strains reducing in the later part of the wetting cycle, showing a path that curves in the opposite sense. The final point of the cycle shows a permanent vertical shrinkage of 0.6% and a permanent radial shrinkage of 0.2% compared to the end of Cycle 1.

The hysteretic pattern of strains observed in Cycle 2 is repeated in Cycles 4 and 5 (wetting data for Cycle 3 is missing). There is also a permanent vertical shrinkage and a permanent radial shrinkage at the end of each cycle, although the magnitude of the shift reduces with the number of cycles.

In the final drying path (Cycle 6) the same curved drying path (as seen in earlier cycles) is followed initially. However, in this final path, drying was continued beyond the limiting water content imposed in Cycles 1-5. As the suction increases beyond that which had been imposed previously (a maximum suction of 670 kPa was imposed during the first drying cycle - this point is indicated by an arrow on

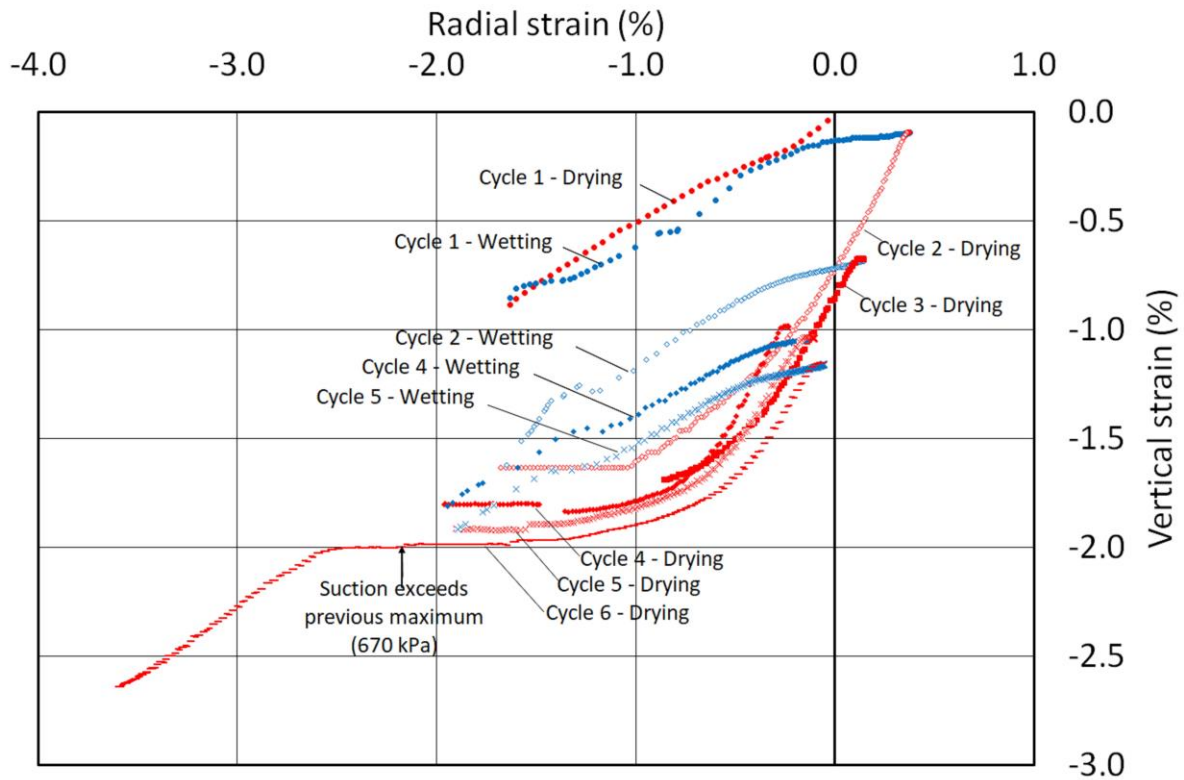


Figure 17) the shape of the curve starts to change significantly. The path continues in an almost linear fashion, with a slope similar to that observed in the first cycle.

These results suggest significant anisotropy of the shrink/swell response. There is significant hysteresis between the drying and wetting strain paths, even though much of the strain is recovered. The magnitude of vertical strain is less than the radial strain response within a hysteretic dry/wet cycle (what can be considered the “elastic response” after wetting). However, there is a permanent change in vertical strain (shrinkage) during drying that is greater than the permanent change in radial strain (also shrinkage), producing an overall downward shift to the response. When the suction exceeds the magnitude applied previously in earlier cycles, the path returns to a linear form, with a slope similar to that observed in the first cycle.

4. Conclusions

A new apparatus was developed that allows continuous measurement of water content, suction and volume change. Volume and matric suction changes subjected to wetting-drying cycles were investigated for a compacted soil obtained from the site of BIONICS experimental embankment in North East England. It was observed that radial and vertical shrinkage of the specimens, dried to the same lowest water content, increased gradually with the number of cycles, and the corresponding matric suction (at the same water content) reduced sharply with the number of cycles.

Different specimens taken from the same larger sample with the same initial water content were found to show different shrinkage rates. For drying and wetting cycles, drying from the same

highest water content, the shrinkage rate decayed very clearly as the number of cycles increased, and the shrinkage rate was nearly the same after the third cycle. The relationship between volume change and matric suction was very similar to that between volume change and water content.

The positions of SWRC curves expressed as gravimetric water content-matric suction curves under wetting-drying cycles shifted downwards with the increase of cycle numbers. However, after 2 or 3 cycles, the difference became steady. This decrease of matric suction may be mainly caused by the decrease in pore size due to shrinkage. Furthermore, the shape of the curves changed obviously under the first three wetting-drying cycles, which means that, even for the same specimen, the SWRC curves should not be represented by a single equation.

Acknowledgements

Funding for this study was provided by the Overseas Study Plan 2009 from the Chinese Academy of Sciences. Mr Stephen Richardson and Mr Kevan Longley in the Department of Engineering (Durham University, UK) manufactured the experimental setup and assisted with data acquisition.

References

- Airò Farulla, C. and Jommi, C. (2005) Suction Controlled Wetting-Drying Cycles on a Compacted Scaly Clay, Proc. Int. Conf. on Problematic Soils, Eastern Mediterranean University, Famagusta, N. Cyprus.
- Airò Farulla, C., Ferrari, A. and Romero, E. (2010) Volume change behaviour of a compacted scaly clay during cyclic suction changes, Canadian Geotechnical Journal, 47(6): 688-703.
- Al Haj, K.M.A. and Standing, J.R. (2016) Soil water retention curves representing two tropical clay soils from Sudan, Géotechnique, 66(1), pp. 71-84 (<https://doi.org/10.1680/jgeot.15.P.086>).
- Al-Mahbashi, A., Elkady, T. and Al-Shamrani, M. (2016). Hysteresis soil-water characteristic curves of highly expansive clay, European Journal of Environmental and Civil Engineering, 3, pp. 1-19, (<https://doi.org/10.1080/19648189.2016.1229232>).
- Alonso E.E., Romero E., Hoffmann C. and García-Escudero E. (2005). Expansive bentonite-sand mixtures in cyclic controlled-suction wetting and drying. Engineering Geology, 81, pp.213-226.
- Boso, M., Romero, E., and Tarantino, A. 2003. The use of different suction measurement techniques to determine water retention curves. In Unsaturated soils: experimental studies. (ed. T. Schanz). Springer-Verlag, Berlin. pp. 171-181.
- Burton, G.J., Pineda, J.A., Sheng, D. and Airey, D. (2015). Microstructural changes of an undisturbed, reconstituted and compacted high plasticity clay subjected to wetting and drying. Engineering Geology, 193(2), pp. 363-373
- Cunningham, M. 2000. The mechanical behaviour of a reconstituted unsaturated soil. Ph.D. thesis, Imperial College of Science, Technology and Medicine, London.
- Dif, A.E. and Bluemel, W.F. (1991). Expansive Soils under Cyclic Drying and Wetting. Geochemical Testing Journal, Vol. 14, No.1, pp.96-102.

- Estabragh, A.R. and Javadi, A.A. (2014). Effect of Soil Density and Suction on the Elastic and Plastic Parameters of Unsaturated Silty Soil. *International Journal of Geomechanics* 15(5), ([https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0000422](https://doi.org/10.1061/(ASCE)GM.1943-5622.0000422)).
- Fleureau, J.M., Verbrugge, J.C. and Huergo, P.J. (2002). Aspects of the behaviour of compacted clayey soils on wetting and drying paths. *Canadian Geotechnical Journal* Vol. 39, pp.1341-1357
- Fredlund D. G. and Rahardjo H. (1993). *Soil Mechanics for Unsaturated Soils*, Soil Mechanics for Unsaturated Soils. Wiley, New York.
- Fredlund D.G. and Xing. A. (1994). Equations for the soil-water characteristic curve. *Canadian Geotechnical Journal*, 31, pp.521-532
- Fredlund, D.G. (2015) Relationship between the laboratory SWCCs and field stress state. Proc. 6th Asia-Pacific Conference on Unsaturated Soil. Guilin, China (eds. Chen, Z.H., Wei, C.F., Sun, D., Xu, Y.F.) London: CRC Press (Taylor & Francis), pp. 1-14.
- Gallage, C., Kodikara, J. and Uchimura, T. (2013). Laboratory measurement of hydraulic conductivity functions of two unsaturated sandy soils during drying and wetting processes. *Soils and Foundations*, 53(3), pp. 417- 430
- Gong Bi-wei, Zhou Xiao-wen and Zhou Wu-hua (2006). Test on suction and strength of expansive soil in a desorption-absorption cycle of moisture. *Chinese Journal of Geotechnical Engineering*, No.2, 28(2), pp. 207-209
- Harrison, B.A. and Blight, G.E. (2000). A comparison of in-situ soil suction measurements. *Unsaturated Soils for Asia, 1st Asian Conference on Unsaturated Soils*, Singapore, Singapore, pp. 281-285
- Hughes, P.N., Glendinning, S., Mendes, J., Parkin, G., Toll, D.G., Gallipoli, D. and Miller, P. (2009). Full-scale testing to assess climate effects on embankments. *Special Issue of Engineering Sustainability: Proc. Institution of Civil Engineers*, Vol. 162, No. 2, pp. 67-79.
- Lourenco, S.D.N. (2008). *Suction Measurements and Water Retention in Unsaturated Soils*. PhD Thesis, Durham University (<http://etheses.dur.ac.uk/1331/>).
- Lourenço, S.D.N., Gallipoli, D., Toll, D.G. and Evans, F.D. (2006) Development of a Commercial Tensiometer for Triaxial Testing of Unsaturated Soils, Proc. 4th International Conference on Unsaturated Soils, Phoenix, USA, *Geotechnical Special Publication No. 147*, Reston: ASCE, Vol.2, pp. 1875-1886.
- Lourenço, S.D.N., Gallipoli, D., Toll, D.G., Augarde, C., Evans, F. and Medero, G. (2008) Calibration of high suction tensiometers, *Géotechnique*, Vol. 58, No. 8, pp. 659-668.
- Lourenço, S.D.N., Gallipoli, D., Toll, D.G., Augarde, C.E. and Evans, F. (2011a). A new procedure for the determination of the Soil Water Retention Curves by continuous drying using high suction tensiometers. *Canadian Geotechnical Journal*, 48,2, pp. 327-335.
- Lourenço, S.D.N., Gallipoli, D., Toll, D.G., Augarde, C. and Evans, F., (2011b). Towards a tensiometer based suction control system for laboratory testing of unsaturated soils. *Geotechnical Testing Journal* 34 (6) [https:// doi.org/10.1520/GTJ103755](https://doi.org/10.1520/GTJ103755).
- McCartney, J. S. and Zornberg J. G. (2010). Effects of infiltration and evaporation on geosynthetic of capillary barrier performance. *Can. Geotech. J.* 47, pp.1201-1213
- Mendes, J. (2011). *Assessment of the Impact of Climate Change on an Instrumented Embankment: An unsaturated soil mechanics approach*, PhD thesis, Durham University (<http://etheses.dur.ac.uk/612/>).
- Noguchi, T., Mendes J. and Toll, D.G. (2012) Comparison of soil water retention curves obtained by filter paper, high capacity suction probe and pressure plate, Proc. 5th Asia-Pacific Conference on Unsaturated Soils, Pataya, Thailand, pp. 368-373.
- Nowamooz, H. and Masrouri, F. (2011). Relationships between soil fabric and suction cycles in

- compacted swelling soils. *Engineering Geology*, 114, pp. 444-455
- Oloo S. Y. and Fredlund D. G. (1995). Matric Suction Monitoring in an Expansive Soil Subgrade In Kenya. 1st Int. Conf. on unsaturated soils, Paris
- Péron, H., Hueckel, T. and Laloui, L. (2007). An improved volume measurement for determining soil water retention curves. *Geotechnical Testing Journal* 30(1), pp. 1–8.
- Pires L. F., Cooper M. and Cássaro F.A.M. (2008). Micromorphological analysis to characterize structure modifications of soil samples submitted to wetting and drying cycles. *Catena* 72 , pp.297-304.
- Tarantino, A., Gallipoli, D., Augarde, C.E., De Gennaro, V., Gomez, R., Laloui, L., Mancuso, C., McCloskey, G., Munoz, J., Pereira, J-M., Peron, H., Pisoni, G., Romero, E., Raveendraraj, A., Rojas, J.C., Toll, D.G., Tombolato, S. and Wheeler, S. (2011) Benchmark of experimental techniques for measuring and controlling suction. *Géotechnique* 61(4), pp. 303–312.
- Teixeira, P.F., and Marinho, F.A.M. 2006. Determination of the soil water retention curve by means of high capacity tensiometers. Proc. 13th Congresso Brasileiro de Mecânica dos Solos e Engenharia Geotécnica, 2006, Curitiba, Brazil. Associação Brasileira de Mecânica dos Solos, Curitiba, Brazil. Vol. 1, pp. 423–427. [in Portuguese.]
- Toker, N., Germaine, J., Sjöblom, K., and Culligan, P. 2004. A new technique for rapid measurement of continuous soil moisture characteristic curves. *Géotechnique*, 54(3), pp. 179–186.
- Toll, D.G. (1999) A Data Acquisition and Control System for Geotechnical Testing, in *Computing Developments in Civil and Structural Engineering* (eds. B. Kumar and B.H.V. Topping), Edinburgh: Civil-Comp Press, pp 237-242.
- Toll, D.G., Asquith, J.D., Fraser, A., Hassan, A.A., Liu, G., Lourenço, S.D.N., Mendes, J., Noguchi, T., Osinski, P. and Stirling, R.A. (2015) Tensiometer techniques for determining soil water retention curves. Proc. 6th Asia-Pacific Conference on Unsaturated Soil. Guilin, China (eds. Chen, Z.H., Wei, C.F., Sun, D., Xu, Y.F.) London: CRC Press (Taylor & Francis), pp. 15-22.
- Toll, D.G., Lourenço, S.D.N. and Mendes, J. (2013) Advances in suction measurements using high suction tensiometers, *Engineering Geology*, Vol. 165, pp29–37.
- Toll, D.G., Mendes, J., Gallipoli, D., Glendinning, S. and Hughes, P.N. (2012) Investigating the Impacts of Climate Change on Slopes: Field Measurements, in *Earthworks in Europe*, Geological Society of London, Special Publication Vol. 26, pp. 151-161.
- Vanapalli S. K., Fredlund D. G. and Pufahl D. E. (1999). The influence of soil structure and stress history on the soil-water characteristics of compacted till. *Geotechnique*, 49(2), pp.143-159.
- Wang Donglin, Luan Maotian and Yang Qing. (2007). Experimental Study On Behaviour Of Unsaturated Remoulded Clay Subjected To Drying And Wetting Cyclic Paths. *Chinese Journal of Rock Mechanics and Engineering*, No.9, 26(9), pp.1862-1867
- Yang Hong, Rahardjo H., Leong, E.C., and Fredlund, D.G.. (2004). Factors affecting wetting and drying soil-water characteristic curves of sandy soils. *Can. Geotech. Jnl.* 41, pp. 908-920
- Yesiller N., Miller C. J. , Inci G. and Yaldo K.. (2000). Desiccation and cracking behavior of three compacted landfill liner soils. *Engineering Geology*, 57, pp. 105-121
- Zhang Fang-zhi and Chen Xiao-ping (2010). Influence of repeated drying and wetting cycles on mechanical behaviors of unsaturated soil. *Chinese Journal of Geotechnical Engineering*, No.1, 32(1), pp.41-46.

Table 1. Physical parameters of testing specimens

Specimen name	Initial water content (%)	Initial degree of saturation (%)	Final water content (%)	Density (Mg/m ³)	Diameter (mm)	Height (mm)
Test0	20.00	89.71	2.14	1.999	75.71	20.83
Test1	19.29	95.36	-	2.058	75.63	20.00
Test2	19.61	96.07	9.06	2.057	75.65	20.07
Test3	19.70	95.25	-	2.049	75.67	19.90
Test4	19.25	95.26	-	2.058	75.70	19.99
Test5	19.55	93.17	10.83	2.036	75.63	19.85
Test6	20.35	92.91	10.10	2.018	75.38	19.87

Figures

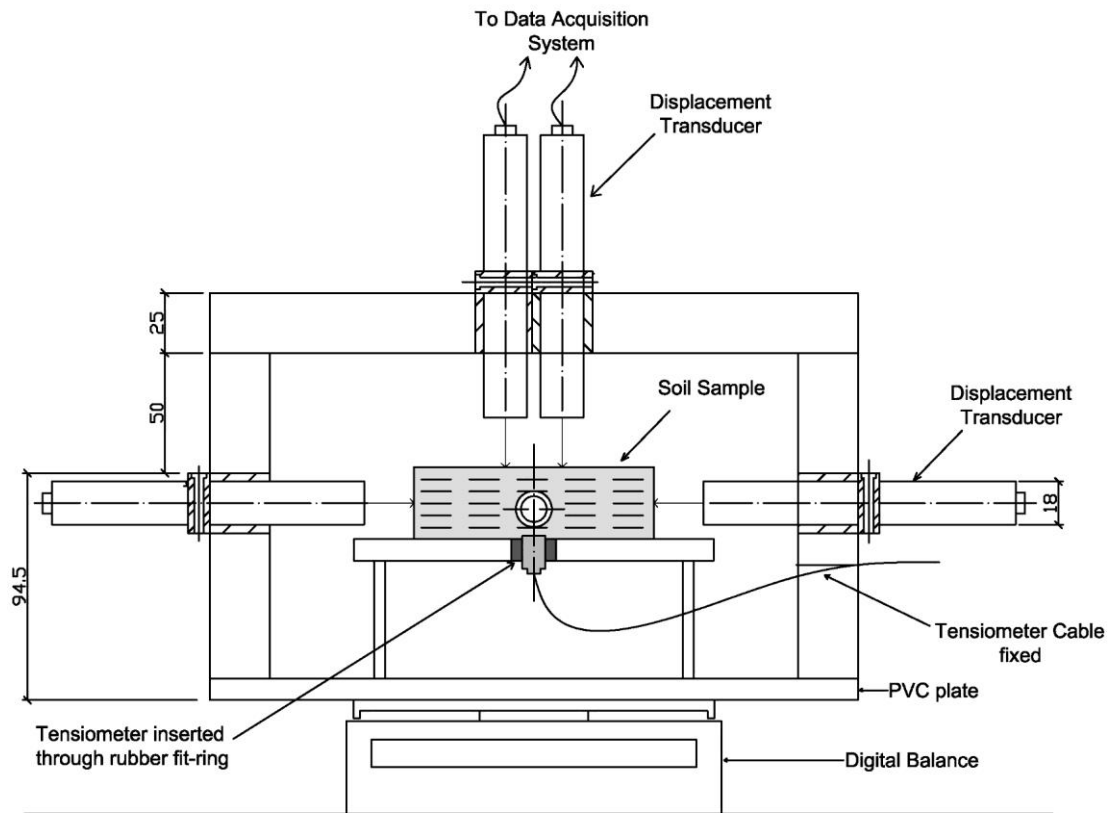


Figure 1. Schematic diagram of experimental setup (dimensions in mm)

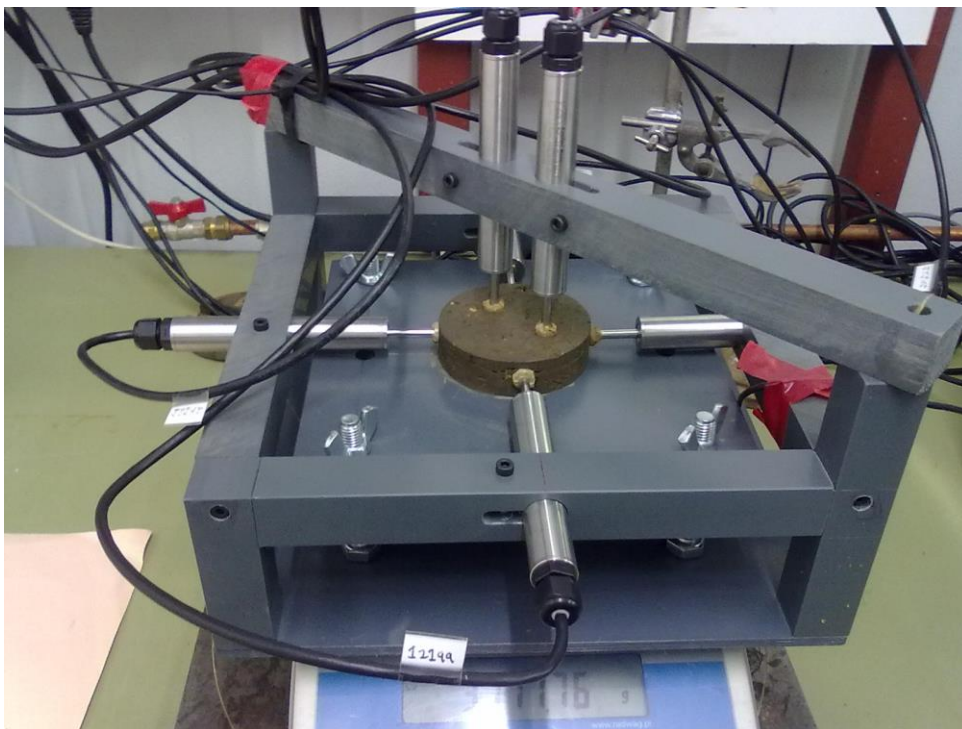


Figure 2. Photograph of the experimental setup

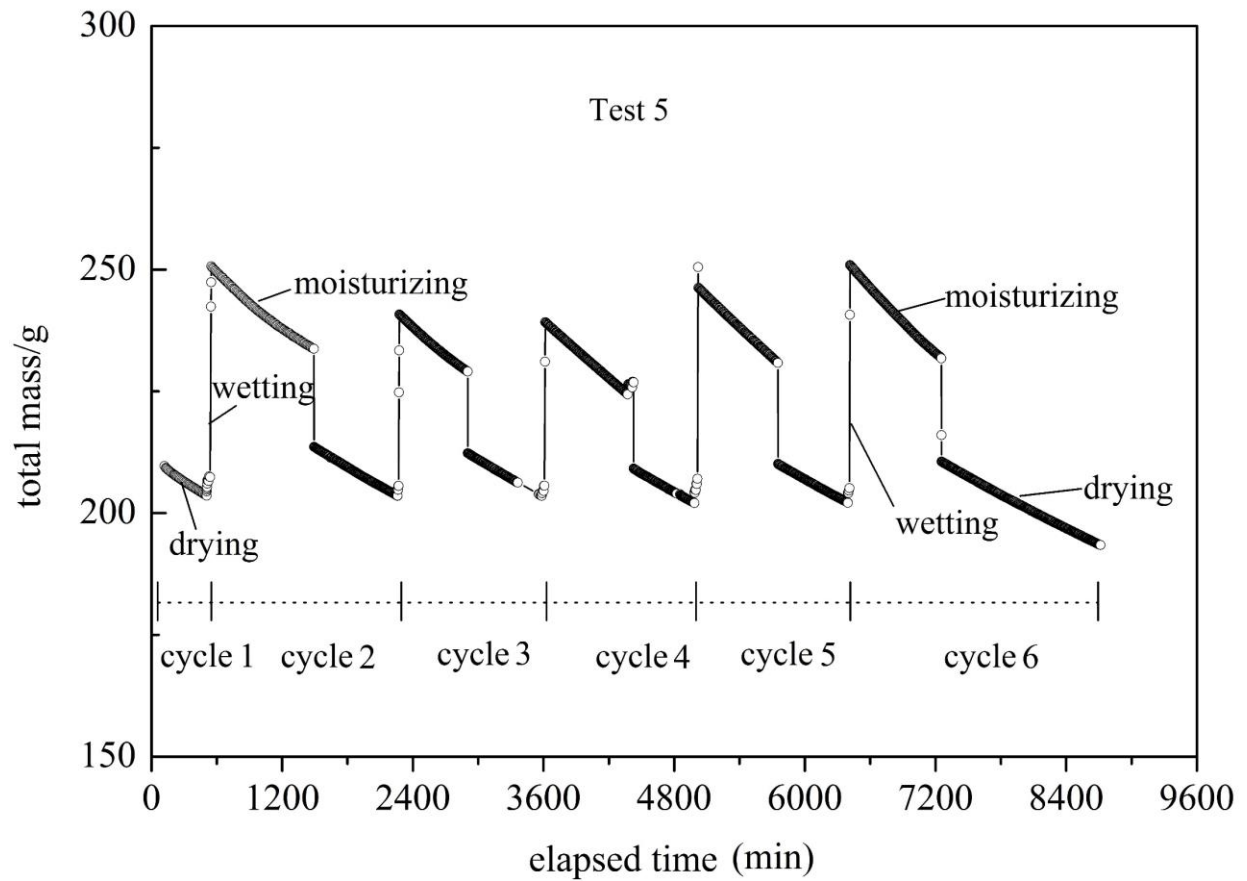


Figure 3. Variations of mass with time in wetting-drying cycles for Test 5

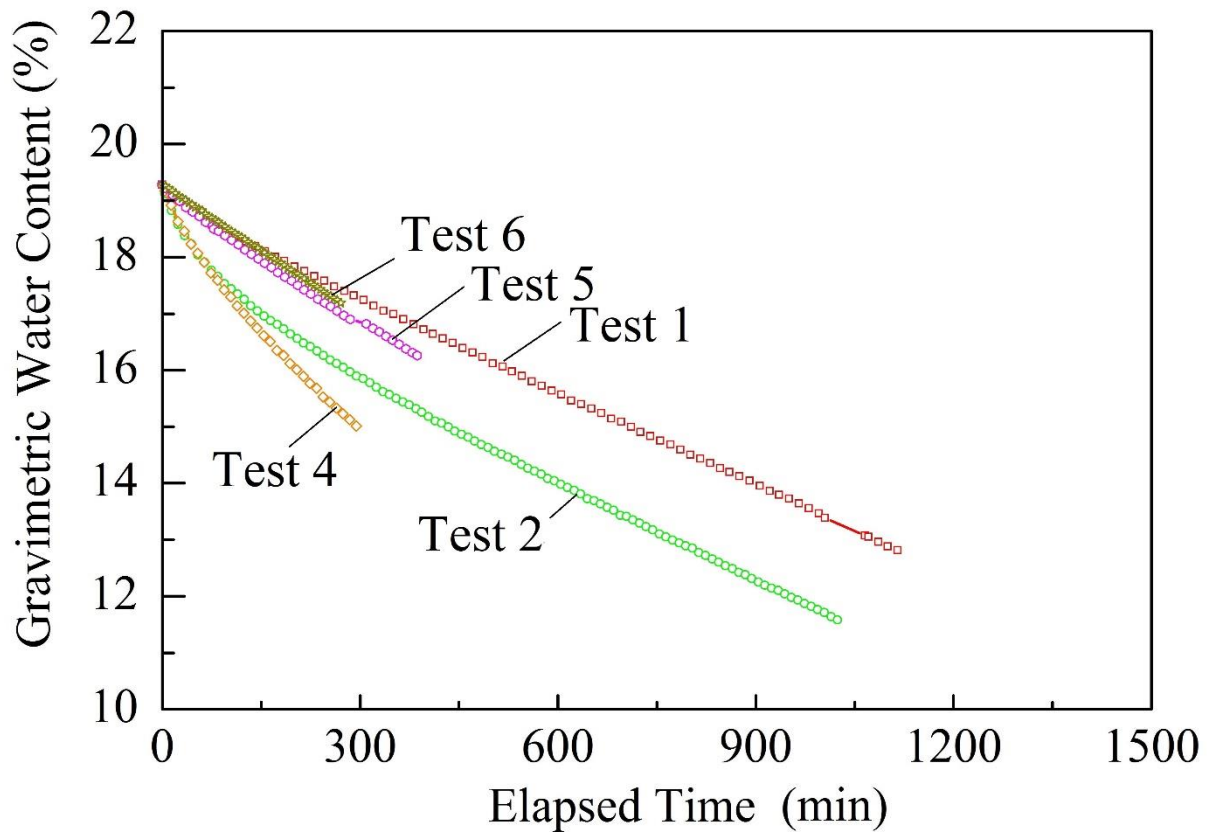


Figure 4. Dehydration curves for 5 specimens

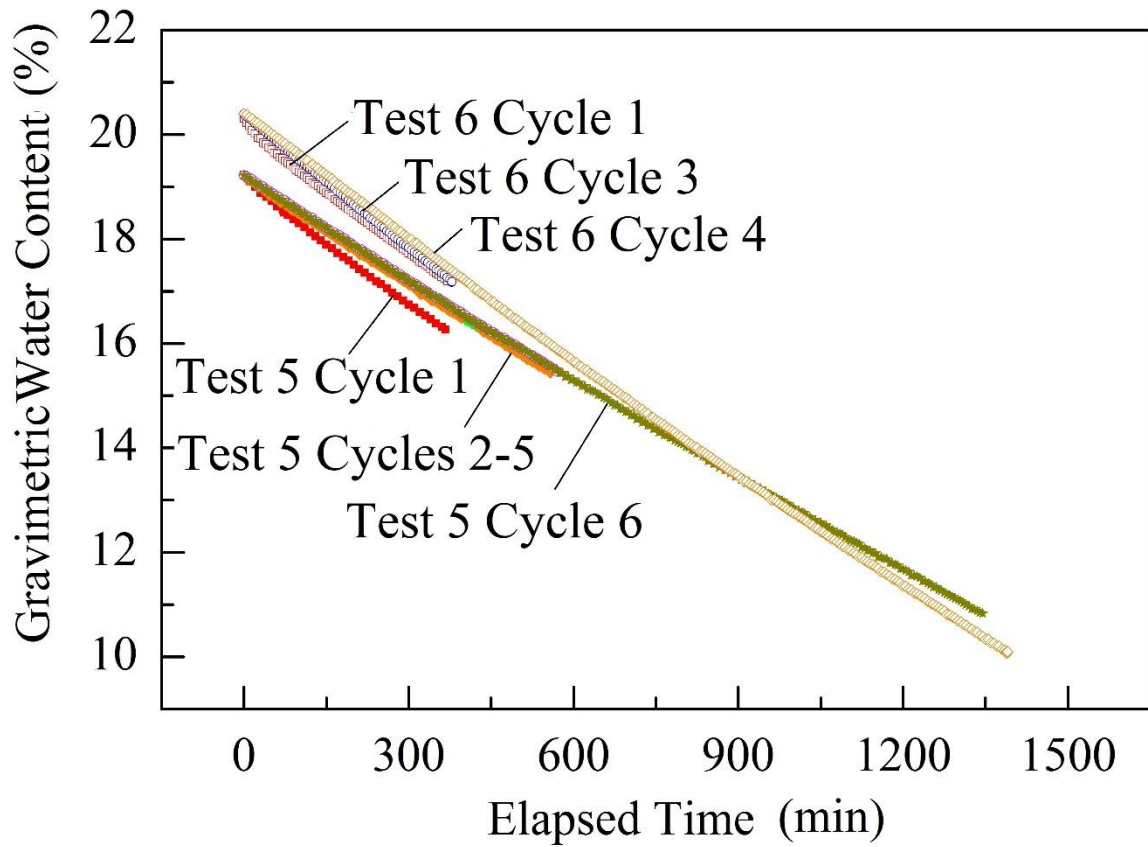


Figure 5. Dehydration curves in drying paths for different cycles of Tests 5 and 6

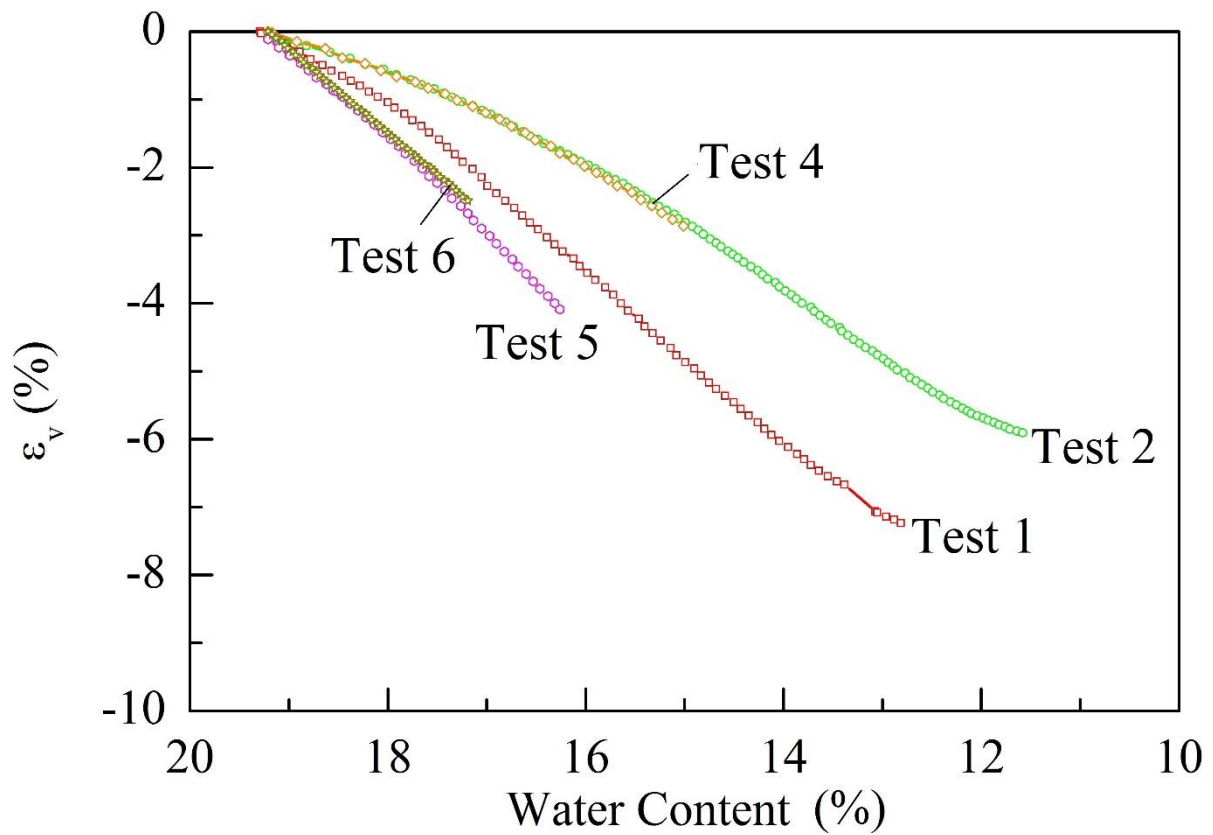


Figure 6. Variation of volume strain with water content in drying paths for 5 specimens (negative values imply a reduction in volume)

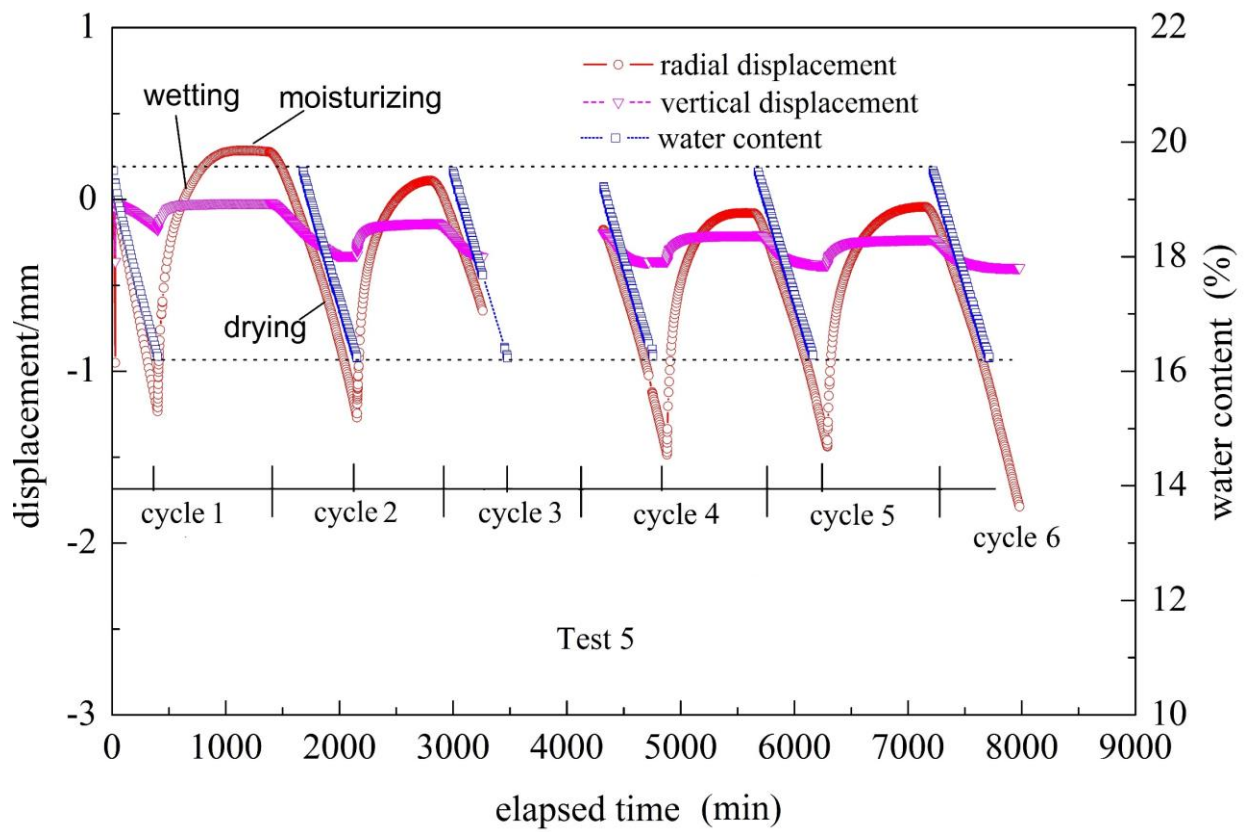


Figure 7. Variations of displacement with time in drying-wetting cycles (Test 5)

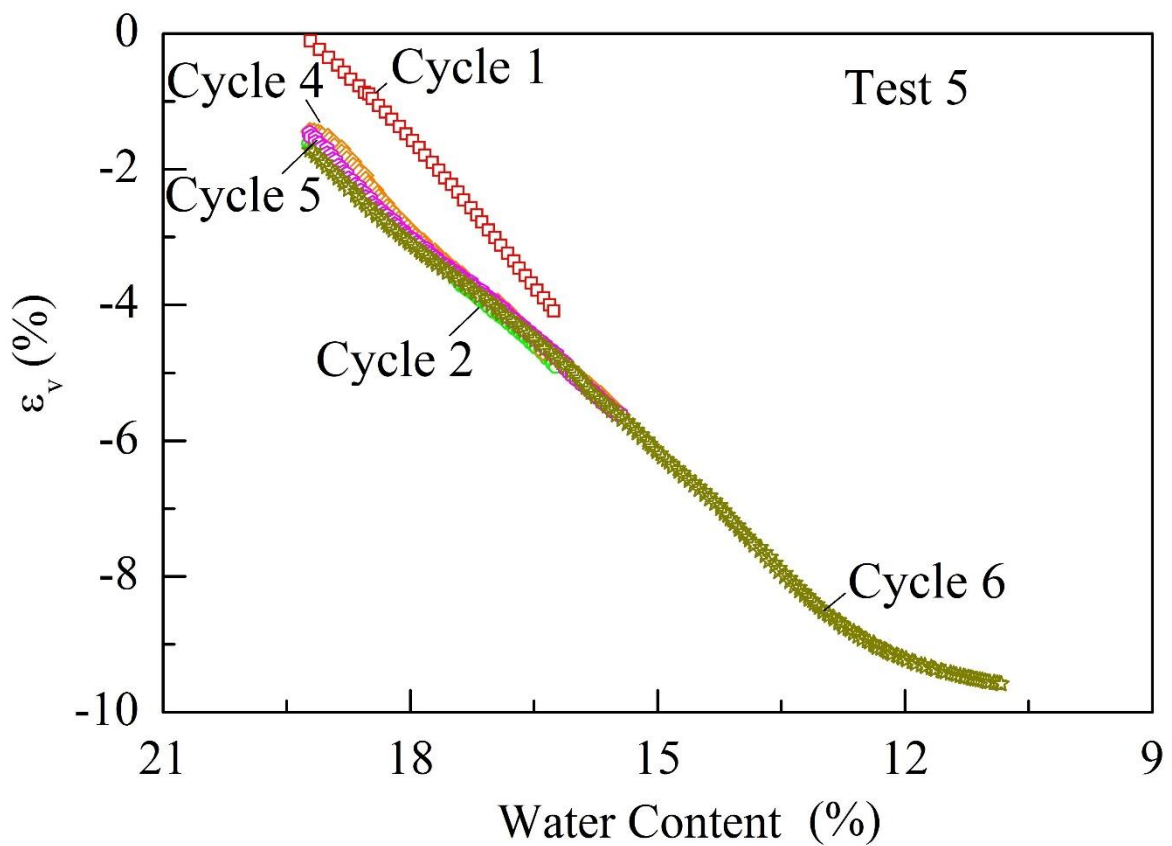


Figure 8. Variation of volume strain with water content in drying paths for Test 5 (negative values imply a reduction in volume)

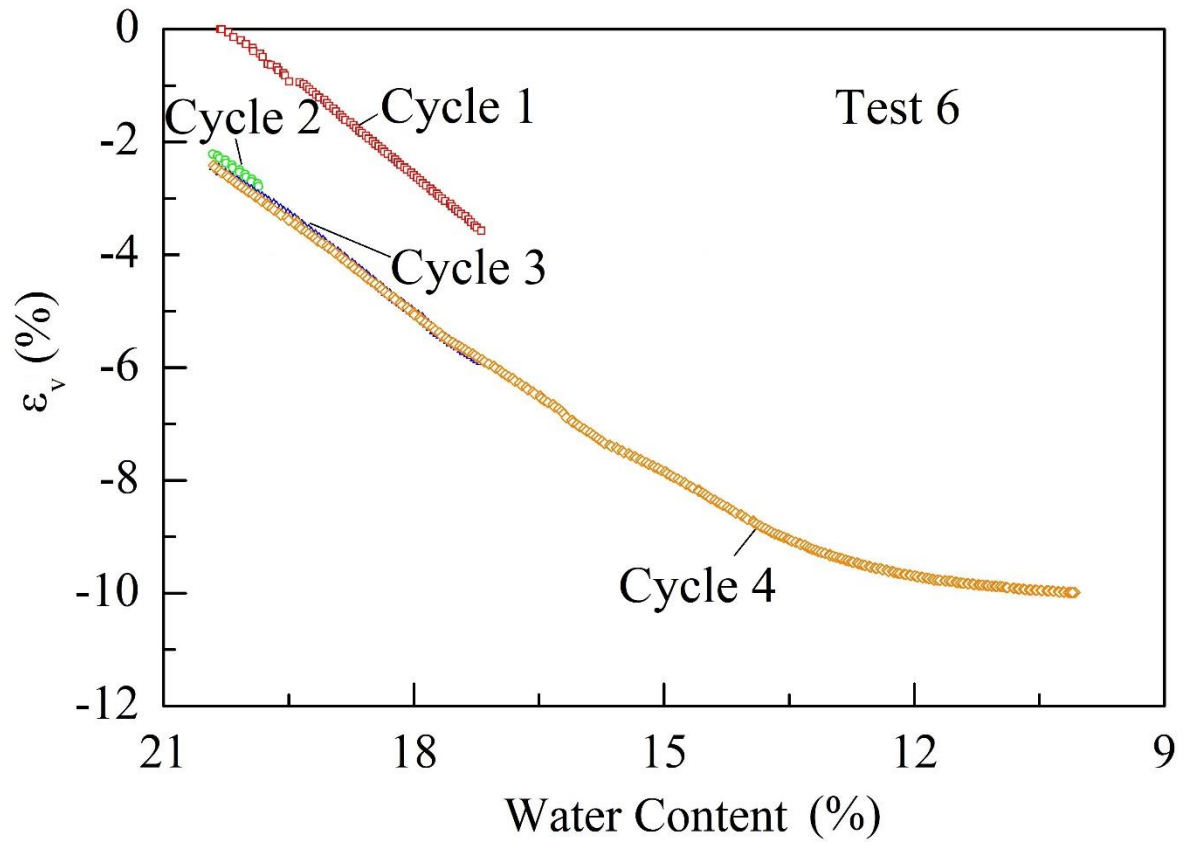


Figure 9. Variation of volume strain with water content in drying paths for Test 6 (negative values imply a reduction in volume)

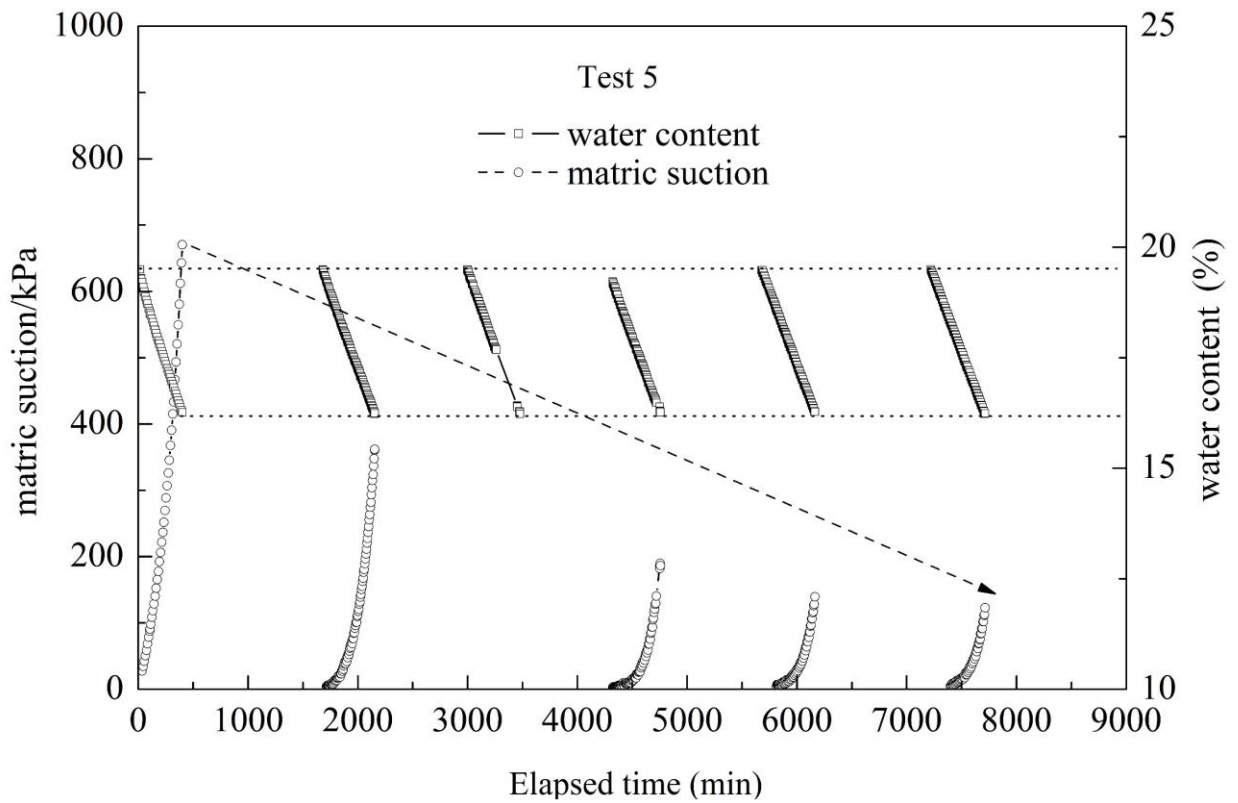


Figure 10. Variations of suction with time in wetting-drying cycles for Test 5

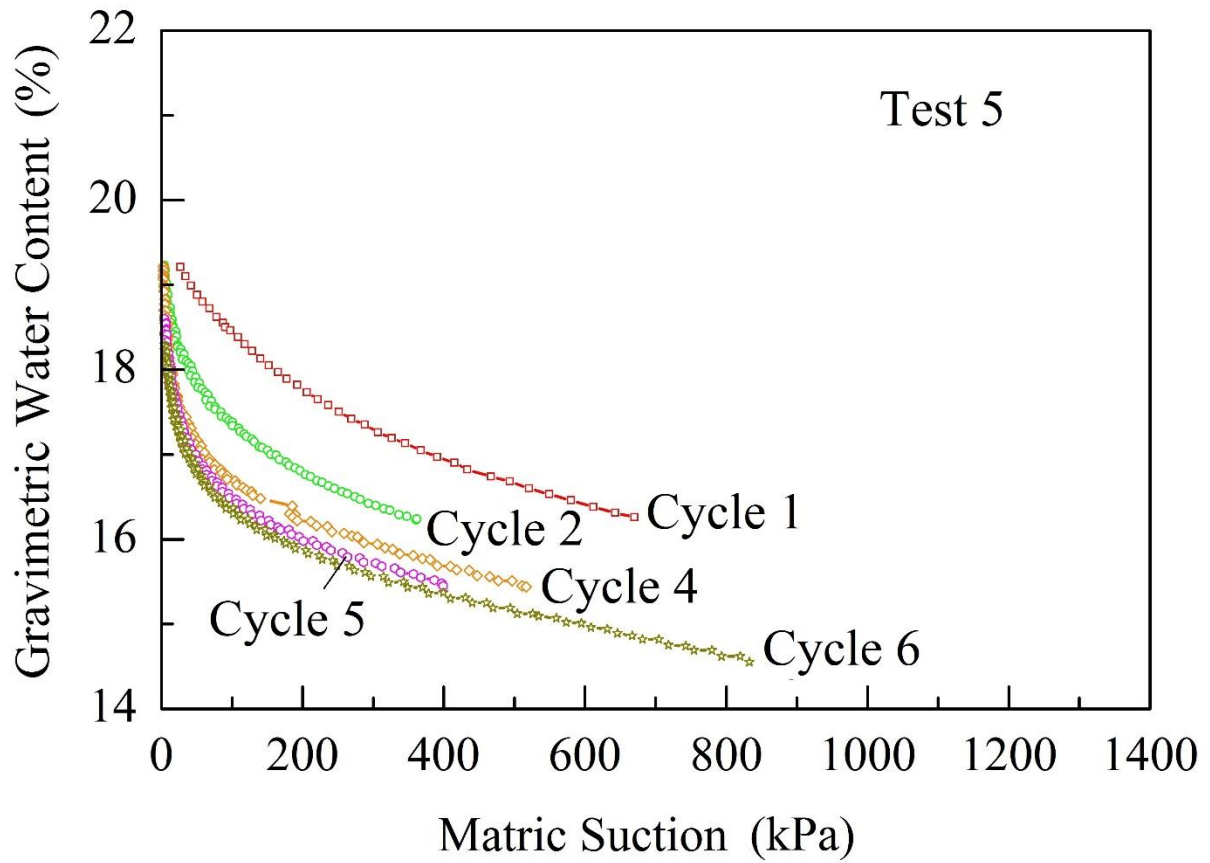


Figure 11. Soil water retention curves (gravimetric water content) in drying-wetting cycles for Test 5

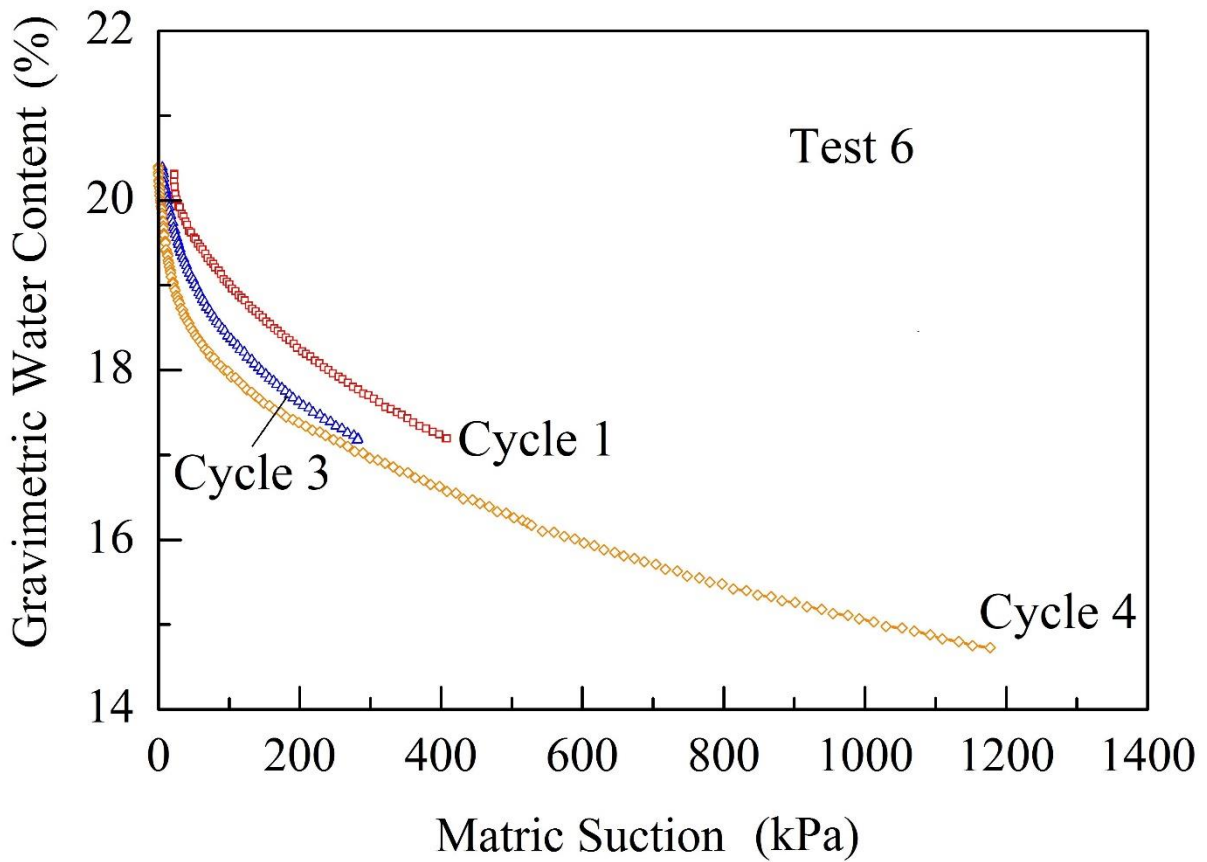


Figure 12. Soil water retention curves (gravimetric water content) in drying-wetting cycles for Test 6

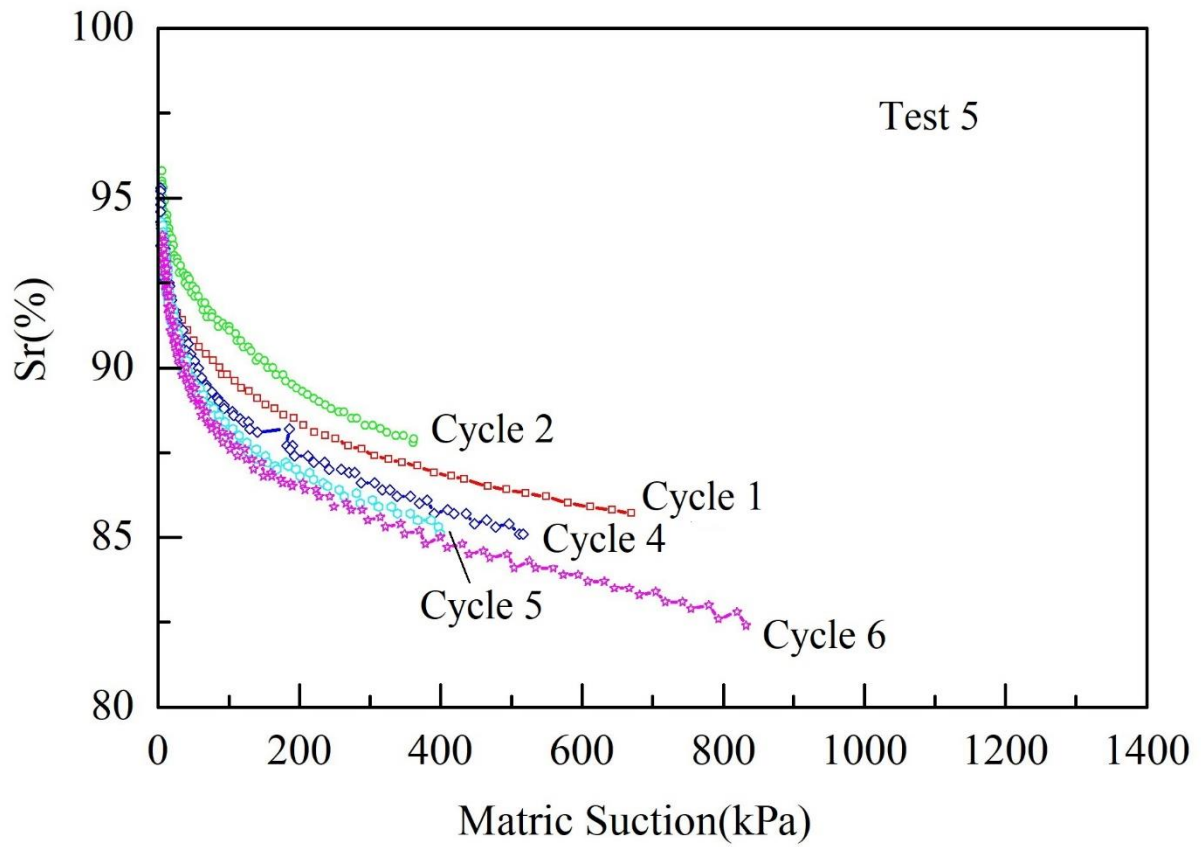


Figure 13. Degree of Saturation change with matric suction in drying-wetting cycles for Test 5

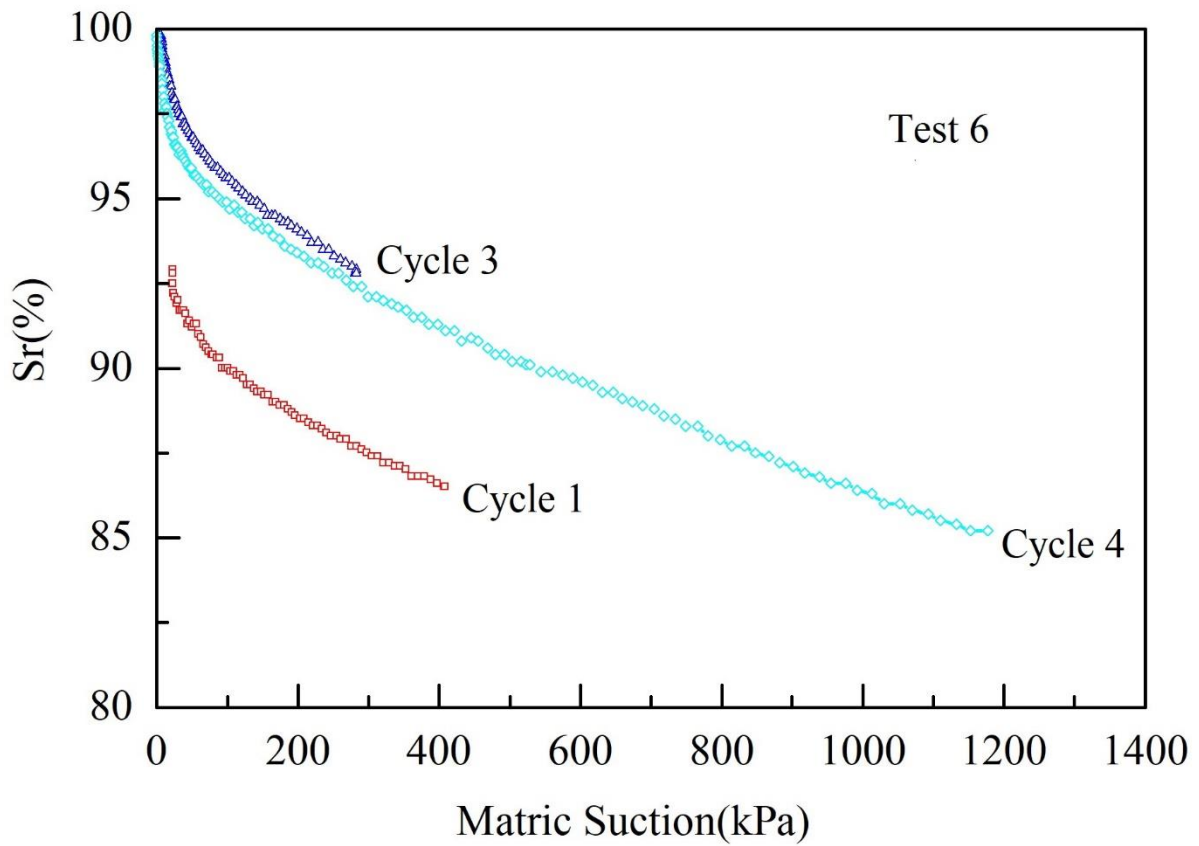


Figure 14. Degree of Saturation change with matric suction in drying-wetting cycles for Test 6

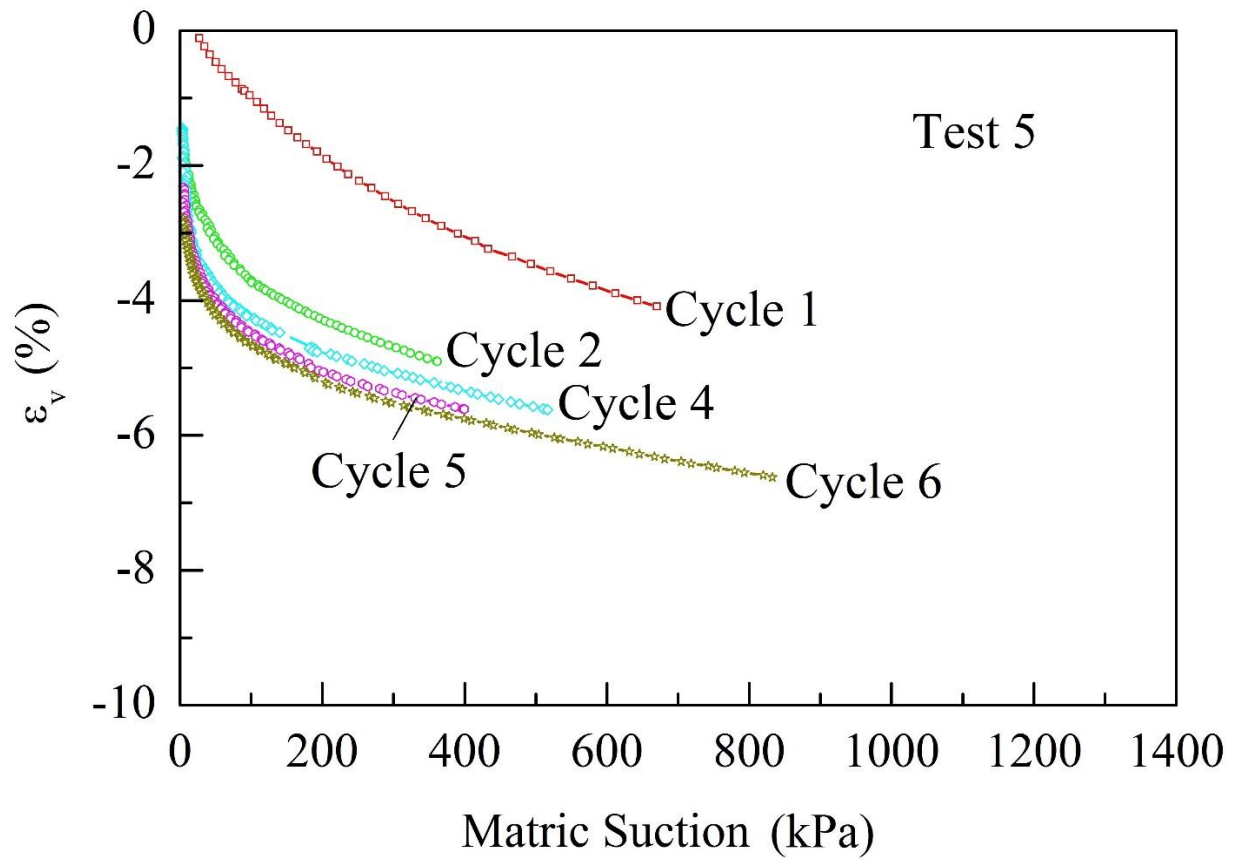


Figure 15. Volume strain change with matric suction in drying-wetting cycles for Test 5

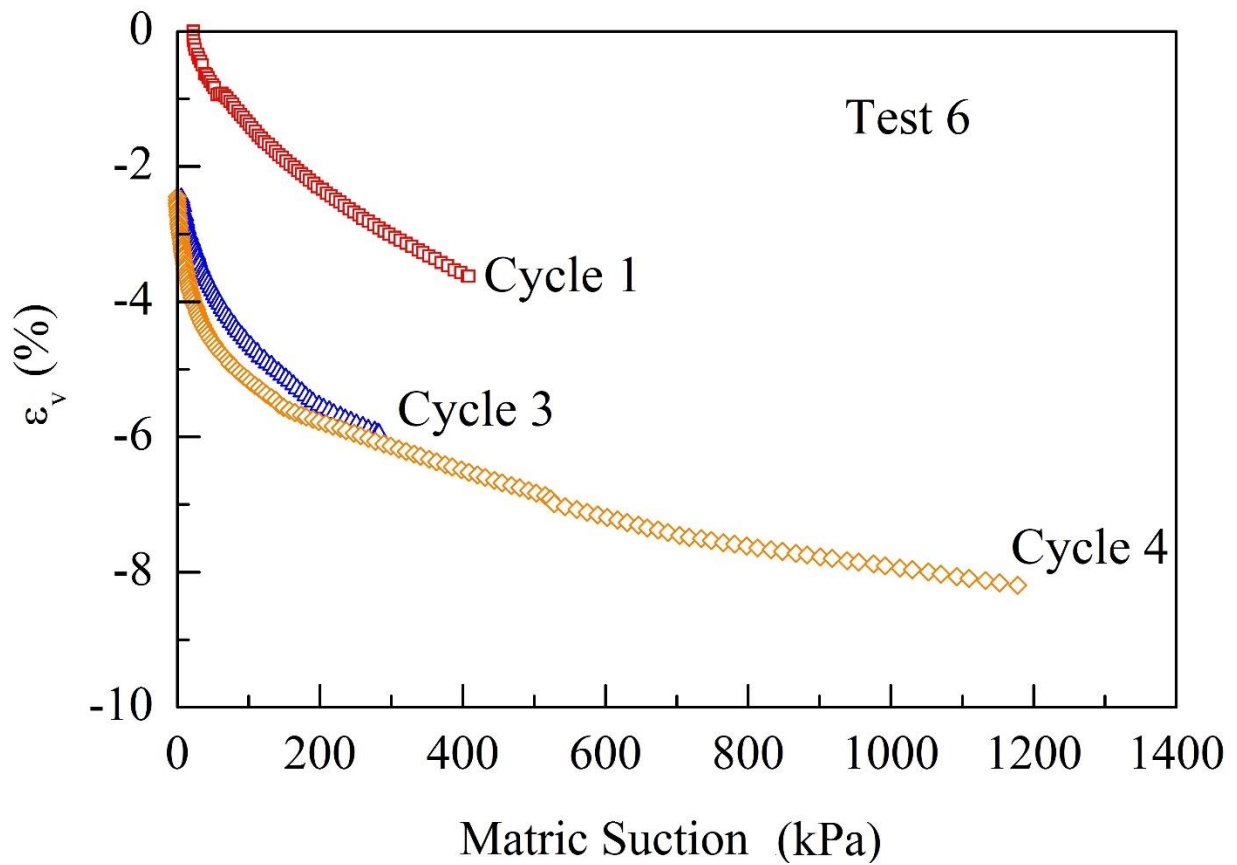


Figure 16. Volume strain change with matric suction in drying-wetting cycles for Test 6

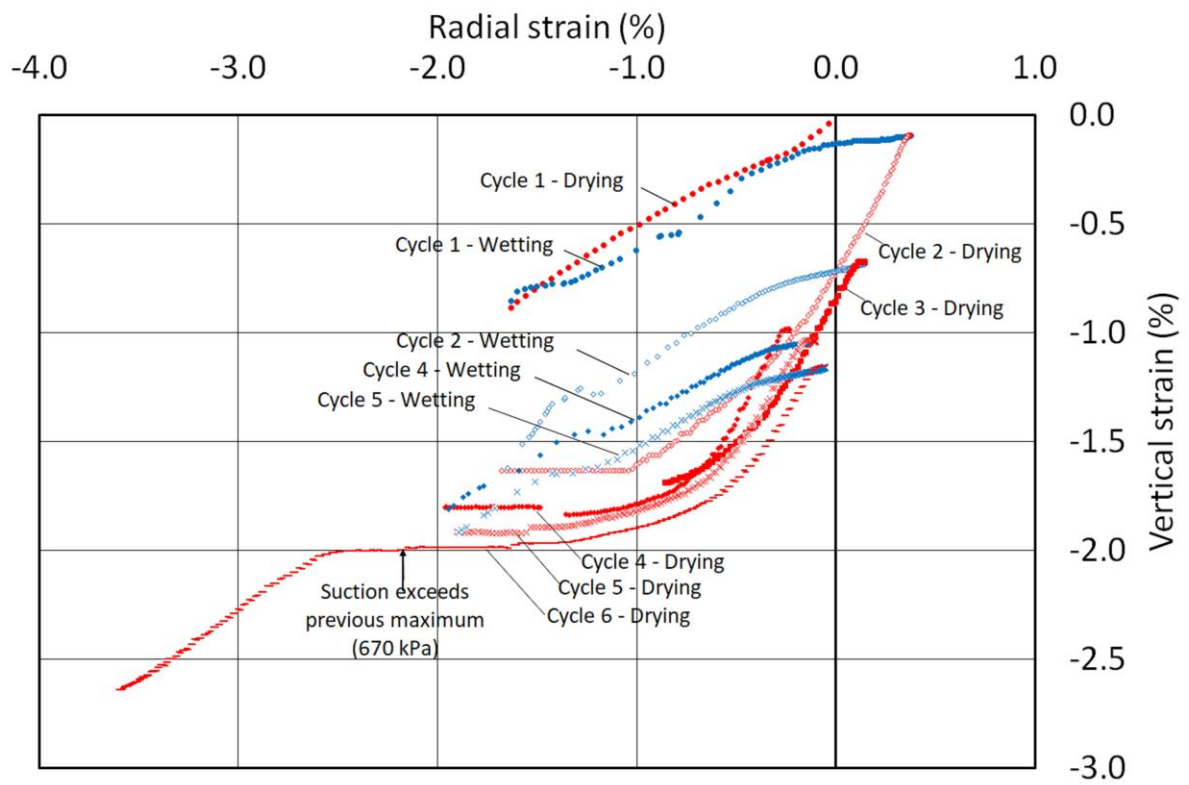


Figure 17. Radial strain vs. vertical strain in drying-wetting cycles for Test 5